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Search for dark matter produced in association with a hadronically decaying vector boson in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration^{*}

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ABSTRACT

A search is presented for dark matter produced in association with a hadronically decaying W or Z boson using 3.2 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV recorded by the ATLAS detector at the Large Hadron Collider. Events with a hadronic jet compatible with a W or Z boson and with large missing transverse momentum are analysed. The data are consistent with the Standard Model predictions and are interpreted in terms of both an effective field theory and a simplified model containing dark matter.

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Dark matter is the dominant component of matter in the universe, but its particle nature remains a mystery. Searches for a weakly interacting massive particle (WIMP), denoted by χ , and for interactions between χ and Standard Model (SM) particles are a central component of the current set of dark-matter experiments.

At particle colliders, dark-matter particles may be produced in pairs via some unknown intermediate state. While in many models direct detection experiments have the greatest sensitivity for dark-matter masses m_χ between 10 and 100 GeV, searches for dark matter at particle colliders are most powerful for lower masses [1–3]. The final-state WIMPs are not directly detectable, but their presence can be inferred from the recoil against a visible particle [1]. Two example processes are shown in Fig. 1.

The Tevatron and LHC collaborations have reported limits on the cross section of $p\bar{p} \rightarrow \chi\bar{\chi} + X$ and $pp \rightarrow \chi\bar{\chi} + X$, respectively, where X is a hadronic jet [1–3], a photon (γ) [4,5], a W/Z boson [6,7], or a Higgs boson [8,9]. In many cases, results are reported in terms of limits on the parameters of an effective field theory (EFT) formulated as a four-point contact interaction [10–18] between quarks and WIMPs. For such models, the strongest limits come from data in which the recoiling object is a jet. In other models, however, the interaction is between dark matter and vector bosons [19], such that the primary discovery mode would be in final states such as those analysed here, where the recoiling object is a W or Z boson.

In this Letter, a search is reported for the production of a W or Z boson decaying hadronically (to $q\bar{q}'$ or $q\bar{q}$, respectively) and reconstructed as a single massive jet in association with large missing transverse momentum from the undetected $\chi\bar{\chi}$ particles in data collected by the ATLAS detector from pp collisions with centre-of-mass energy $\sqrt{s} = 13$ TeV. This search is sensitive to WIMP pair production, as well as to other dark-matter-related models which predict invisible Higgs boson decays (WH or ZH production with $H \rightarrow \chi\bar{\chi}$).

The ATLAS detector [20] at the LHC covers the pseudorapidity¹ range $|\eta| < 4.9$ and the full azimuthal angle ϕ . It consists of an inner tracking detector surrounded by a superconducting solenoid, electromagnetic and hadronic calorimeters, and an external muon spectrometer incorporating large superconducting toroidal magnets. A two-level trigger system is used to select interesting events to be recorded for subsequent offline analysis. Only data for which beams were stable and all subsystems described above were operational are used. Applying these requirements to pp collision data, recorded during the 2015 LHC run, results in a data sample with a time-integrated luminosity of 3.2 fb^{-1} . The systematic uncertainty

¹ ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z -axis along the beam pipe. The x -axis points from the IP to the centre of the LHC ring, and the y -axis points upward. Polar coordinates (r, ϕ) are used in the transverse (x, y) plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$.

^{*} E-mail address: atlas.publications@cern.ch.

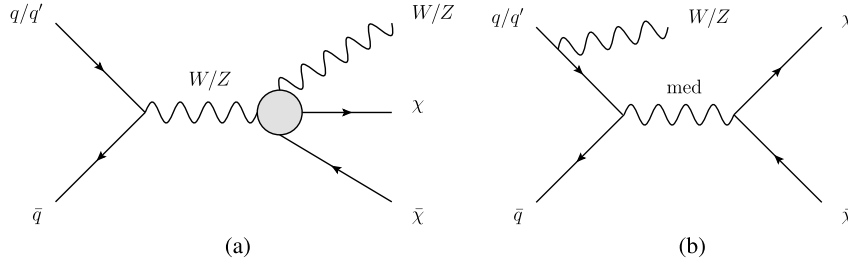


Fig. 1. Pair production of WIMPs ($\chi\bar{\chi}$) in proton–proton collisions at the LHC in association with a vector boson (V , meaning W or Z) via two hypothetical processes: (a) production via an effective $VV\chi\chi$ interaction or (b) via a simplified model which includes an s -channel mediator.

of 2.1% in the luminosity is derived following the same methodology as that detailed in Ref. [21].

Three non-exclusive categories of jet candidates are built, each using the anti- k_{\perp} clustering algorithm [22]. Two categories use clusters of energy deposits in calorimeter cells seeded by those with energies significantly above the measured noise and calibrated at the hadronic energy scale [25]. They are distinguished by their radius parameters; jets with radius parameter of 1.0 (0.4) are referred to as *large- R jets* (*narrow jets*). Large and narrow jets can share a fraction of their energy deposits. A third type of jet candidate is reconstructed from inner-detector tracks using the anti- k_{\perp} algorithm with $R = 0.2$, referred to as *track jets*. Large- R jets are trimmed [26] to remove energy deposited by pile-up jets, the underlying event, and soft radiation. In this process, the constituents of large- R jets are reclustered using the k_{\perp} algorithm [23,24] with a distance parameter of 0.2, and subjets with transverse momentum p_T less than 5% of the large- R jet p_T are removed. Large- R jets are required to satisfy $p_T > 200$ GeV and $|\eta| < 2.0$. These large- R jets are intended to capture the hadronic products of both quarks from the decay of a W or Z boson, while the narrow jets and track jets are helpful in background suppression. The internal structure of the large- R jet is characterized in terms of two quantities: D_2 [27,28], which identifies jets with two distinct concentrations of energy [29,30], and m_{jet} , which is the calculated invariant mass of the jet. Narrow jets are required to satisfy $p_T > 20$ GeV for $|\eta| < 2.5$ or $p_T > 30$ GeV for $2.5 < |\eta| < 4.5$. Track jets are required to satisfy $p_T > 10$ GeV and $|\eta| < 2.5$. For both the large- R and narrow jets, jet momenta are calculated by performing a four-vector sum over these component clusters, treating each topological cluster [25] as an (E, \vec{p}) four-vector with zero mass, and are calibrated to the hadronic scale. For narrow jets, the direction of \vec{p} is given by the line joining the reconstructed vertex with the barycentre of the energy cluster. The missing transverse momentum $\mathbf{E}_T^{\text{miss}}$ is calculated as the negative of the vector sum of the transverse momenta of reconstructed jets, leptons, and those tracks which are associated with the reconstructed vertex but not with any jet or lepton. A closely related quantity, $\mathbf{E}_{T,\text{no}\mu}^{\text{miss}}$, is calculated in the same way but excluding reconstructed muons. A third variant, $\mathbf{p}_T^{\text{miss}}$, is the missing transverse momentum measured using inner detector tracks. The magnitudes of the three missing-transverse-momentum variants are denoted by E_T^{miss} , $E_{T,\text{no}\mu}^{\text{miss}}$, and p_T^{miss} , respectively. Electrons, muons, jets, and $\mathbf{E}_T^{\text{miss}}$ are reconstructed as described in Refs. [25, 31–33], respectively.

Candidate signal events are selected by an inclusive $\mathbf{E}_T^{\text{miss}}$ trigger that is more than 99% efficient for events with $E_T^{\text{miss}} > 200$ GeV. Events triggered by detector noise and non-collision backgrounds are rejected as described in Ref. [34]. In addition, events are required to satisfy the requirements of $E_T^{\text{miss}} > 250$ GeV, no reconstructed electrons or muons, and at least one large- R jet with $p_T > 200$ GeV, $|\eta| < 2.0$, m_{jet} and D_2 consistent with a W or Z boson decay as in Ref. [35]. To further suppress back-

grounds from multijet and $t\bar{t}$ production, events are required to satisfy $p_T^{\text{miss}} > 30$ GeV, a minimum azimuthal angular distance, $\Delta\phi$, of 0.6 between the $\mathbf{E}_T^{\text{miss}}$ and the nearest narrow jet, and $\Delta\phi(\mathbf{E}_T^{\text{miss}}, \mathbf{p}_T^{\text{miss}}) < \pi/2$. Within a fiducial volume defined at parton level by similar selection requirements (except those on D_2 and p_T^{miss}), the reconstruction efficiency for the signal models described above varies from 38% to 49%.

The dominant source of background events is $Z \rightarrow \nu\bar{\nu}$ production in association with jets. A secondary contribution comes from the production of jets in association with a leptonically decaying W or Z boson in which the charged leptons are not identified or the τ leptons decay hadronically. The third major background contribution comes from top-quark pair production. The kinematic distributions of these three largest backgrounds are estimated using simulated event samples but the normalization is determined using control regions where the dark-matter signal is expected to be negligible. Each control region requires $E_T^{\text{miss}} > 200$ GeV and $p_T^{\text{miss}} > 30$ GeV as well as one large- R jet satisfying the substructure requirement on D_2 as applied in the signal region. The Z boson control region requires exactly two muons with dimuon invariant mass $66 < m_{\mu\mu} < 116$ GeV. The W boson (top quark) control region requires exactly one muon, and zero (at least one) b -tagged track jet not associated with the large- R jet. Validation of the reconstruction of hadronic W boson decays with large- R jets is performed in the top-quark control region, as shown in Fig. 2, which also presents the distribution of the D_2 substructure variable. Other sources of background are diboson production and single-top-quark production. The contribution to the signal region from multijet production is negligible.

Samples of simulated W + jets and Z + jets events are generated using SHERPA 2.1.1 [36]. Matrix elements are calculated for up to two partons at next-to-leading order (NLO) and four partons at leading order (LO) using the Comix [37] and OpenLoops [38] matrix element generators and merged with the SHERPA parton shower [39] using the ME+PS@NLO prescription [40]. The CT10 [41] PDF set is used in conjunction with dedicated parton shower tuning developed by the SHERPA authors. The W/Z production rates are normalized to a next-to-next-to-leading order (NNLO) calculation [42]. The production of $t\bar{t}$ and single-top processes, including s -channel, t -channel and Wt production is modelled with the POWHEG-Box v2 generator [43–45] interfaced to PYTHIA6.428 [46]. In these generators the CT10 and CTEQ6L1 [47] PDF sets are used, respectively. Top-quark pair production is normalized to NNLO with next-to-next-to-leading-logarithm corrections [48] in QCD while single-top processes are normalized at NLO [49,50] in QCD. The diboson (WW, WZ, ZZ) processes are simulated using SHERPA 2.1.1 with the CT10 PDF and normalized at NLO [51,52] in QCD. The multijet process is described using samples simulated with PYTHIA8.186 [53] and the NNPDF2.3LO [54] PDF at leading order in QCD; these multijet samples were used to develop the background estimation strategy but not for the final background prediction.

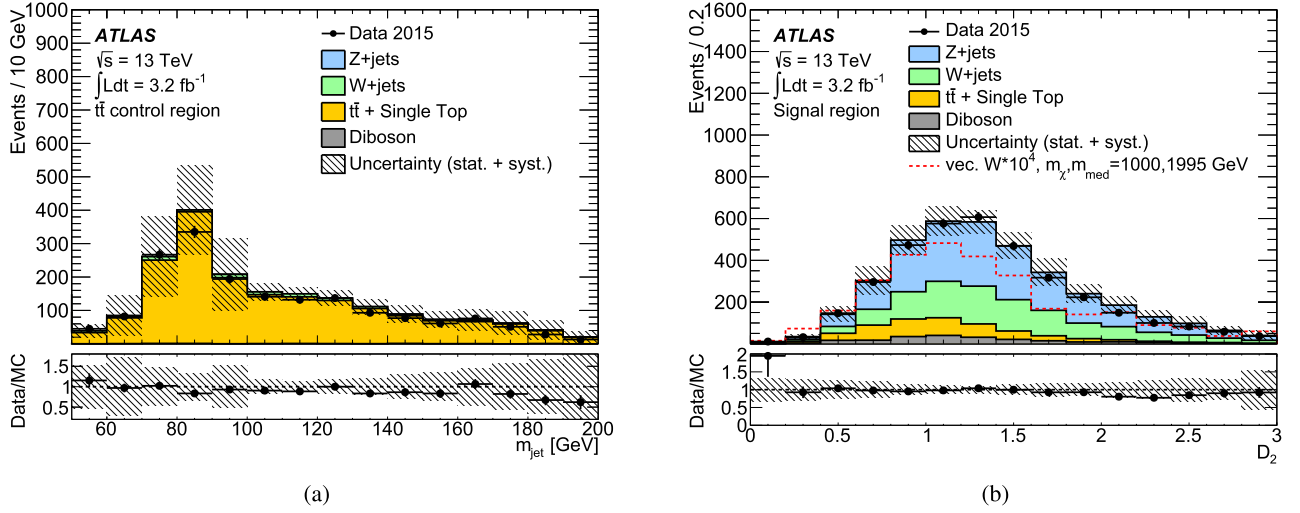


Fig. 2. Pane (a) Distribution of m_{jet} in the data and for the predicted background in the top-quark control region. Pane (b) Distribution of jet substructure variable D_2 in the data and for the predicted background in events satisfying all signal region requirements other than those on D_2 . Also shown is the distribution for the simplified model with a vector-boson mediator, scaled by a factor of 10^4 for given values of m_χ and m_{med} , the mediator mass. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

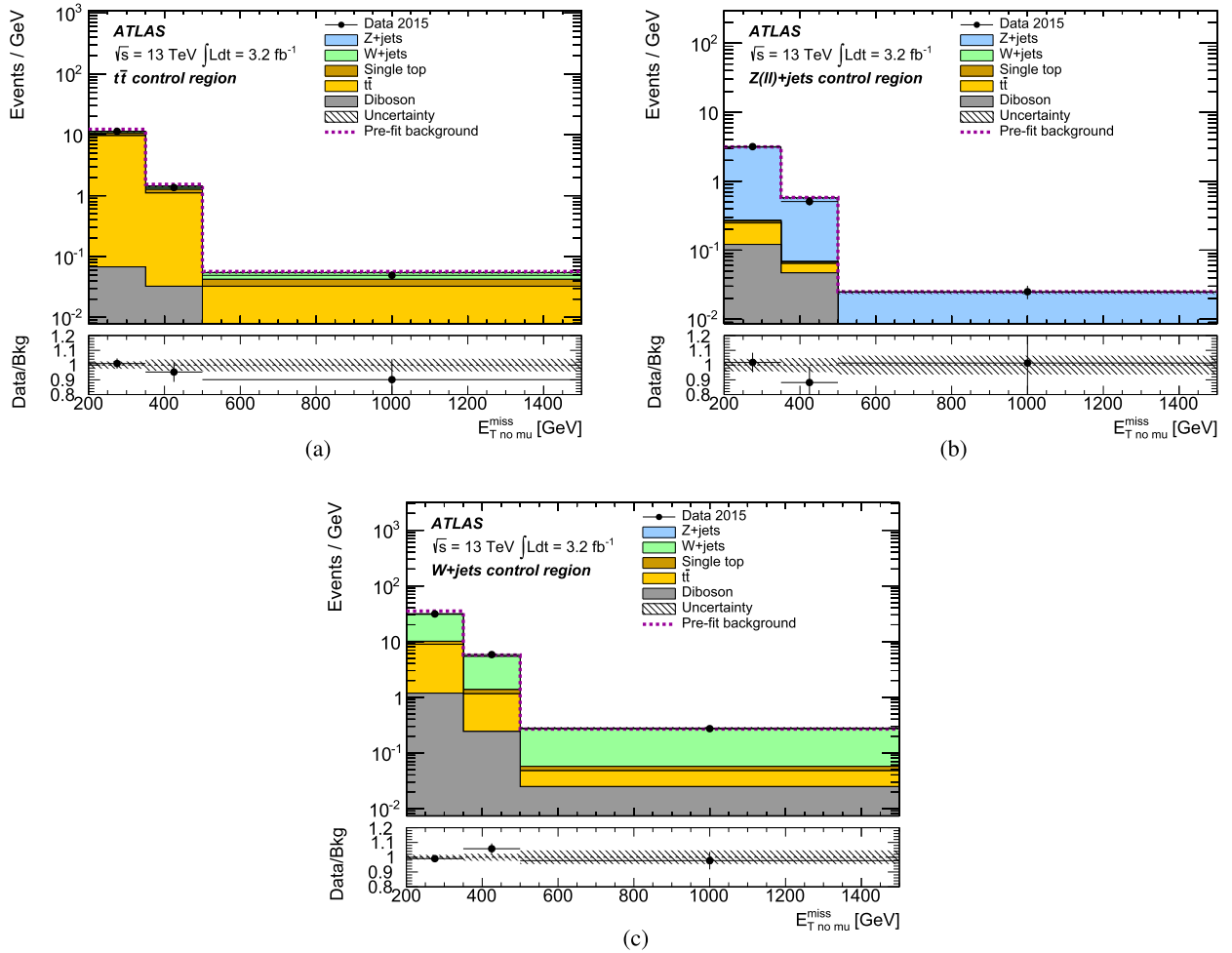


Fig. 3. The E_T^{miss} distribution of the events in the control regions after the profile-likelihood fit to the data under the background-only hypothesis. Pane (a) shows the $t\bar{t}$ control region, pane (b) shows the $Z + \text{jets}$ control region, and pane (c) shows the $W + \text{jets}$ control region. The total background prediction before the fit is shown as a dashed line. The inset at the bottom of each plot shows the ratio of the data to the total post-fit background. The hatched bands represent the total uncertainty in the background. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

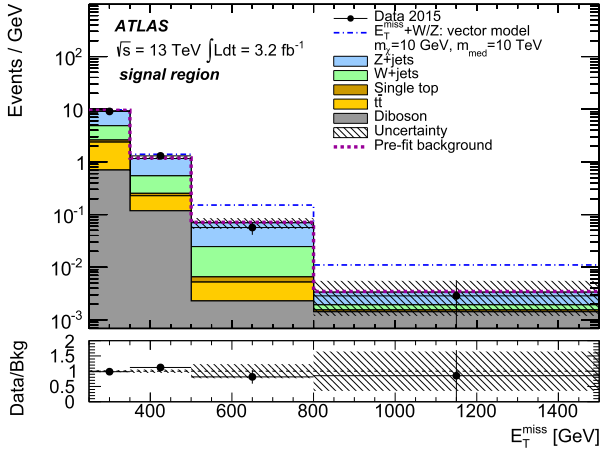


Fig. 4. The E_T^{miss} distribution of the events in the signal region after the profile-likelihood fit to the data under the background-only hypothesis. The inset shows the ratio of the data to the total background. Also shown is the E_T^{miss} distribution for the simplified model with a vector-boson mediator, scaled by a factor of 10^4 for $m_\chi = 10$ GeV and $m_{\text{med}} = 10$ TeV. The total background before the fit is shown as a dashed line. The hatched bands represent the total uncertainty in the background. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Samples of simulated $W\chi\bar{\chi}$ and $Z\chi\bar{\chi}$ events are generated using MADGRAPH5_AMC@NLO [55], and the underlying event and parton showering are simulated with PYTHIA8.186 [53]. Two theoretical models are used as benchmarks: a seven-dimensional $VV\chi\chi$ EFT [19] model (V meaning W or Z) and a vector-mediated simplified model [56]. The strength of the EFT interaction is controlled by a mass scale, M_\star , and the strength of the simplified model interaction is controlled by the product of the couplings of the mediator to the SM and the dark matter (DM) particles, $g_{\text{SM}}g_{\text{DM}}$. The EFT model samples were generated with $M_\star = 3000$ GeV, and the simplified model samples were generated with couplings $g_{\text{SM}} = 0.25$ and $g_{\text{DM}} = 1$. The samples were generated as a function of dark-matter particle mass m_χ for the EFT model and in a grid of mediator mass m_{med} and m_χ for the simplified model.

Major sources of systematic uncertainty are uncertainties in the modelling of large- R jet observables, which have a 5–13% impact on the expected background and signal yields, and the energy scale of the narrow jets, which contribute a 1–5% uncertainty to the expected yields. Other sources of uncertainty include theoretical uncertainties in the simulated event samples used to model the background processes (1–10%), parton distribution functions (10–15%), and lepton reconstruction and identification efficiencies (up to 2%).

A profile-likelihood fit [57] to the E_T^{miss} ($E_{T,\text{no}\mu}^{\text{miss}}$) distribution in the signal region (control regions) is used to constrain the W boson, Z boson, and $t\bar{t}$ backgrounds and extract the signal strength, μ , for each model as an overall normalization factor for the signal prediction. Besides the signal strength, three overall normalization factors for the W boson, Z boson, and $t\bar{t}$ backgrounds are parameters in the fit. The diboson and single-top backgrounds are estimated from simulation, and the multijet background is negligible. The likelihood function is defined as the product of Poisson distributions over all bins in E_T^{miss} and $E_{T,\text{no}\mu}^{\text{miss}}$, and the likelihood is simultaneously maximized over the signal and control regions.

Variations of the expected signal and background to allow for their systematic uncertainties are described with nuisance parameters constrained by Gaussian probability distribution functions, and correlations across signal and background processes and regions are taken into account.

Table 1

Predicted and observed number of events in the signal region. The yields and uncertainties of the backgrounds are shown after the profile-likelihood fit to the data under the background-only hypothesis. For comparison, the expected yield in the $VV\chi\chi$ EFT model with $M_\star = 600$ GeV and $m_\chi = 500$ GeV is 10.1 ± 0.4 events.

Process	Events
$Z + \text{jets}$	544 ± 33
$W + \text{jets}$	275 ± 24
$t\bar{t}$ and single-top	211 ± 19
Diboson	89 ± 12
Total background	1120 ± 47
Data	1121

Table 2

Background normalization factors relative to the initial theoretical prediction, extracted from the profile-likelihood fit under the background-only hypothesis.

Process	Normalization factor
$Z + \text{jets}$	1.01 ± 0.16
$W + \text{jets}$	0.90 ± 0.16
$t\bar{t}$	0.91 ± 0.18

A background-only ($\mu = 0$) fit, shows no deviation from SM predictions, and Figs. 3 and 4 show kinematic distributions after the profile-likelihood fit. The floating background-normalization parameters are consistent with unity within one standard deviation. Tables 1 and 2 show the expected event yields after applying the signal selection and the background normalization scale factors, respectively. The values in these tables are estimated for the background-only hypothesis.

Upper limits at 95% confidence level (C.L.) on μ are calculated using the CL_s method [58]. For the $VV\chi\chi$ EFT model, these limits are translated into constraints on the mass scale, M_\star . Fig. 5(a) shows the limit on the mass scale, M_\star , in the EFT model, as a function of m_χ . Fig. 5(b) shows the limits on the signal strength, μ , for a vector-mediated simplified model generated with couplings $g_{\text{SM}} = 0.25$ and $g_{\text{DM}} = 1$ in the plane of m_χ and m_{med} .

In conclusion, this Letter reports ATLAS limits on dark-matter production in events with a hadronically decaying W or Z boson and large missing transverse momentum. These limits from 3.2 fb^{-1} of 13 TeV pp collisions at the LHC improve on earlier ATLAS results. No statistically significant excess is observed over the Standard Model prediction.

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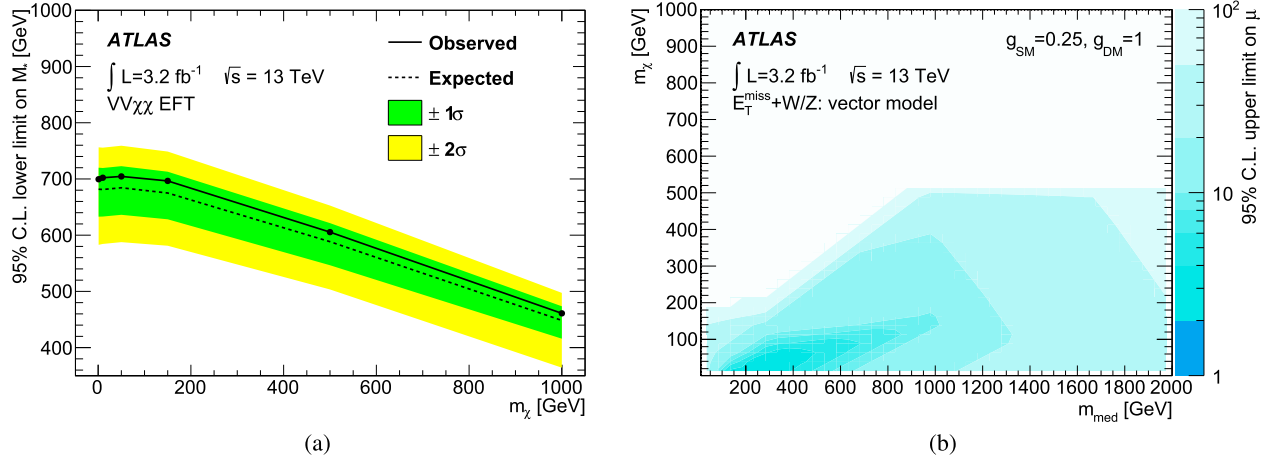


Fig. 5. Pane (a) shows the limit on the mass scale, M_* , of the $VV\chi\chi$ EFT model. Pane (b) shows the observed limit on the signal strength, μ , of the vector-mediated simplified model in the plane of the dark-matter particle mass, m_χ , and the mediator mass, m_{med} ; white areas indicate an upper limit at $\mu \geq 100$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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The ATLAS Collaboration

M. Aaboud^{136d}, G. Aad⁸⁷, B. Abbott¹¹⁴, J. Abdallah⁸, O. Abdinov¹², B. Abeloos¹¹⁸, R. Aben¹⁰⁸, O.S. AbouZeid¹³⁸, N.L. Abraham¹⁵², H. Abramowicz¹⁵⁶, H. Abreu¹⁵⁵, R. Abreu¹¹⁷, Y. Abulaiti^{149a,149b}, B.S. Acharya^{168a,168b,a}, S. Adachi¹⁵⁸, L. Adamczyk^{40a}, D.L. Adams²⁷, J. Adelman¹⁰⁹, S. Adomeit¹⁰¹, T. Adye¹³², A.A. Affolder⁷⁶, T. Agatonovic-Jovin¹⁴, J. Agricola⁵⁶, J.A. Aguilar-Saavedra^{127a,127f}, S.P. Ahlen²⁴, F. Ahmadov^{67,b}, G. Aielli^{134a,134b}, H. Akerstedt^{149a,149b}, T.P.A. Åkesson⁸³, A.V. Akimov⁹⁷, G.L. Alberghi^{22a,22b}, J. Albert¹⁷³, S. Albrand⁵⁷, M.J. Alconada Verzini⁷³, M. Aleksa³², I.N. Aleksandrov⁶⁷, C. Alexa^{28b}, G. Alexander¹⁵⁶, T. Alexopoulos¹⁰, M. Alhroob¹¹⁴, B. Ali¹²⁹, M. Aliev^{75a,75b}, G. Alimonti^{93a}, J. Alison³³, S.P. Alkire³⁷, B.M.M. Allbrooke¹⁵², B.W. Allen¹¹⁷, P.P. Allport¹⁹, A. Aloisio^{105a,105b}, A. Alonso³⁸, F. Alonso⁷³, C. Alpigiani¹³⁹, A.A. Alshehri⁵⁵, M. Alstady⁸⁷, B. Alvarez Gonzalez³², D. Álvarez Piqueras¹⁷¹, M.G. Alviggi^{105a,105b}, B.T. Amadio¹⁶, K. Amako⁶⁸, Y. Amaral Coutinho^{26a}, C. Amelung²⁵, D. Amidei⁹¹, S.P. Amor Dos Santos^{127a,127c}, A. Amorim^{127a,127b}, S. Amoroso³², G. Amundsen²⁵, C. Anastopoulos¹⁴², L.S. Ancu⁵¹, N. Andari¹⁹, T. Andeen¹¹, C.F. Anders^{60b}, G. Anders³², J.K. Anders⁷⁶, K.J. Anderson³³, A. Andreazza^{93a,93b}, V. Andrei^{60a}, S. Angelidakis⁹, I. Angelozzi¹⁰⁸, P. Anger⁴⁶, A. Angerami³⁷, F. Anghinolfi³², A.V. Anisenkov^{110,c}, N. Anjos¹³, A. Annovi^{125a,125b}, C. Antel^{60a}, M. Antonelli⁴⁹, A. Antonov^{99,*}, F. Anulli^{133a}, M. Aoki⁶⁸, L. Aperio Bella¹⁹, G. Arabidze⁹², Y. Arai⁶⁸, J.P. Araque^{127a}, A.T.H. Arce⁴⁷, F.A. Arduh⁷³, J.-F. Arguin⁹⁶, S. Argyropoulos⁶⁵, M. Arik^{20a}, A.J. Armbruster¹⁴⁶, L.J. Armitage⁷⁸, O. Arnaez³², H. Arnold⁵⁰, M. Arratia³⁰, O. Arslan²³, A. Artamonov⁹⁸, G. Artoni¹²¹, S. Artz⁸⁵, S. Asai¹⁵⁸, N. Asbah⁴⁴, A. Ashkenazi¹⁵⁶, B. Åsman^{149a,149b}, L. Asquith¹⁵², K. Assamagan²⁷, R. Astalos^{147a}, M. Atkinson¹⁷⁰, N.B. Atlay¹⁴⁴, K. Augsten¹²⁹, G. Avolio³², B. Axen¹⁶, M.K. Ayoub¹¹⁸, G. Azuelos^{96,d}, M.A. Baak³², A.E. Baas^{60a}, M.J. Baca¹⁹, H. Bachacou¹³⁷, K. Bachas^{75a,75b}, M. Backes¹²¹, M. Backhaus³², P. Bagiacchi^{133a,133b}, P. Bagnaia^{133a,133b}, Y. Bai^{35a}, J.T. Baines¹³², O.K. Baker¹⁸⁰, E.M. Baldin^{110,c}, P. Balek¹⁷⁶, T. Balestri¹⁵¹, F. Balli¹³⁷, W.K. Balunas¹²³, E. Banas⁴¹, Sw. Banerjee^{177,e}, A.A.E. Bannoura¹⁷⁹, L. Barak³², E.L. Barberio⁹⁰, D. Barberis^{52a,52b}, M. Barbero⁸⁷, T. Barillari¹⁰², M.-S. Barisits³², T. Barklow¹⁴⁶, N. Barlow³⁰, S.L. Barnes⁸⁶, B.M. Barnett¹³², R.M. Barnett¹⁶, Z. Barnovska-Blenessy⁵, A. Baroncelli^{135a}, G. Barone²⁵, A.J. Barr¹²¹, L. Barranco Navarro¹⁷¹, F. Barreiro⁸⁴, J. Barreiro Guimarães da Costa^{35a}, R. Bartoldus¹⁴⁶, A.E. Barton⁷⁴, P. Bartos^{147a}, A. Basalaev¹²⁴, A. Bassalat^{118,f}, R.L. Bates⁵⁵, S.J. Batista¹⁶², J.R. Batley³⁰, M. Battaglia¹³⁸,

M. Bauce^{133a,133b}, F. Bauer¹³⁷, H.S. Bawa^{146,g}, J.B. Beacham¹¹², M.D. Beattie⁷⁴, T. Beau⁸², P.H. Beauchemin¹⁶⁶, P. Bechtle²³, H.P. Beck^{18,h}, K. Becker¹²¹, M. Becker⁸⁵, M. Beckingham¹⁷⁴, C. Becot¹¹¹, A.J. Beddall^{20e}, A. Beddall^{20b}, V.A. Bednyakov⁶⁷, M. Bedognetti¹⁰⁸, C.P. Bee¹⁵¹, L.J. Beemster¹⁰⁸, T.A. Beermann³², M. Begel²⁷, J.K. Behr⁴⁴, C. Belanger-Champagne⁸⁹, A.S. Bell⁸⁰, G. Bella¹⁵⁶, L. Bellagamba^{22a}, A. Bellerive³¹, M. Bellomo⁸⁸, K. Belotskiy⁹⁹, O. Beltramello³², N.L. Belyaev⁹⁹, O. Benary^{156,*}, D. Bencheekroun^{136a}, M. Bender¹⁰¹, K. Bendtz^{149a,149b}, N. Benekos¹⁰, Y. Benhammou¹⁵⁶, E. Benhar Noccioli¹⁸⁰, J. Benitez⁶⁵, D.P. Benjamin⁴⁷, J.R. Bensinger²⁵, S. Bentvelsen¹⁰⁸, L. Beresford¹²¹, M. Beretta⁴⁹, D. Berge¹⁰⁸, E. Bergeaas Kuutmann¹⁶⁹, N. Berger⁵, J. Beringer¹⁶, S. Berlendis⁵⁷, N.R. Bernard⁸⁸, C. Bernius¹¹¹, F.U. Bernlochner²³, T. Berry⁷⁹, P. Berta¹³⁰, C. Bertella⁸⁵, G. Bertoli^{149a,149b}, F. Bertolucci^{125a,125b}, I.A. Bertram⁷⁴, C. Bertsche⁴⁴, D. Bertsche¹¹⁴, G.J. Besjes³⁸, O. Bessidskaia Bylund^{149a,149b}, M. Bessner⁴⁴, N. Besson¹³⁷, C. Betancourt⁵⁰, A. Bethani⁵⁷, S. Bethke¹⁰², A.J. Bevan⁷⁸, R.M. Bianchi¹²⁶, L. Bianchini²⁵, M. Bianco³², O. Biebel¹⁰¹, D. Biedermann¹⁷, R. Bielski⁸⁶, N.V. Biesuz^{125a,125b}, M. Biglietti^{135a}, J. Bilbao De Mendizabal⁵¹, T.R.V. Billoud⁹⁶, H. Bilokon⁴⁹, M. Bindi⁵⁶, S. Binet¹¹⁸, A. Bingul^{20b}, C. Bini^{133a,133b}, S. Biondi^{22a,22b}, T. Bisanz⁵⁶, D.M. Bjergaard⁴⁷, C.W. Black¹⁵³, J.E. Black¹⁴⁶, K.M. Black²⁴, D. Blackburn¹³⁹, R.E. Blair⁶, J.-B. Blanchard¹³⁷, T. Blazek^{147a}, I. Bloch⁴⁴, C. Blocker²⁵, A. Blue⁵⁵, W. Blum^{85,*}, U. Blumenschein⁵⁶, S. Blunier^{34a}, G.J. Bobbink¹⁰⁸, V.S. Bobrovnikov^{110,c}, S.S. Bocchetta⁸³, A. Bocci⁴⁷, C. Bock¹⁰¹, M. Boehler⁵⁰, D. Boerner¹⁷⁹, J.A. Bogaerts³², D. Bogavac¹⁴, A.G. Bogdanchikov¹¹⁰, C. Bohm^{149a}, V. Boisvert⁷⁹, P. Bokan¹⁴, T. Bold^{40a}, A.S. Boldyrev^{168a,168c}, M. Bomben⁸², M. Bona⁷⁸, M. Boonekamp¹³⁷, A. Borisov¹³¹, G. Borissov⁷⁴, J. Bortfeldt³², D. Bortoletto¹²¹, V. Bortolotto^{62a,62b,62c}, K. Bos¹⁰⁸, D. Boscherini^{22a}, M. Bosman¹³, J.D. Bossio Sola²⁹, J. Boudreau¹²⁶, J. Bouffard², E.V. Bouhova-Thacker⁷⁴, D. Boumediene³⁶, C. Bourdarios¹¹⁸, S.K. Boutle⁵⁵, A. Boveia³², J. Boyd³², I.R. Boyko⁶⁷, J. Bracinik¹⁹, A. Brandt⁸, G. Brandt⁵⁶, O. Brandt^{60a}, U. Bratzler¹⁵⁹, B. Brau⁸⁸, J.E. Brau¹¹⁷, W.D. Breaden Madden⁵⁵, K. Brendlinger¹²³, A.J. Brennan⁹⁰, L. Brenner¹⁰⁸, R. Brenner¹⁶⁹, S. Bressler¹⁷⁶, T.M. Bristow⁴⁸, D. Britton⁵⁵, D. Britzger⁴⁴, F.M. Brochu³⁰, I. Brock²³, R. Brock⁹², G. Brooijmans³⁷, T. Brooks⁷⁹, W.K. Brooks^{34b}, J. Brosamer¹⁶, E. Brost¹⁰⁹, J.H. Broughton¹⁹, P.A. Bruckman de Renstrom⁴¹, D. Bruncko^{147b}, R. Bruneliere⁵⁰, A. Bruni^{22a}, G. Bruni^{22a}, L.S. Bruni¹⁰⁸, B.H. Brunt³⁰, M. Bruschi^{22a}, N. Bruscino²³, P. Bryant³³, L. Bryngemark⁸³, T. Buanes¹⁵, Q. Buat¹⁴⁵, P. Buchholz¹⁴⁴, A.G. Buckley⁵⁵, I.A. Budagov⁶⁷, F. Buehrer⁵⁰, M.K. Bugge¹²⁰, O. Bulekov⁹⁹, D. Bullock⁸, H. Burckhart³², S. Burdin⁷⁶, C.D. Burgard⁵⁰, B. Burghgrave¹⁰⁹, K. Burka⁴¹, S. Burke¹³², I. Burmeister⁴⁵, J.T.P. Burr¹²¹, E. Busato³⁶, D. Büscher⁵⁰, V. Büscher⁸⁵, P. Bussey⁵⁵, J.M. Butler²⁴, C.M. Buttar⁵⁵, J.M. Butterworth⁸⁰, P. Butti¹⁰⁸, W. Buttinger²⁷, A. Buzatu⁵⁵, A.R. Buzykaev^{110,c}, S. Cabrera Urbán¹⁷¹, D. Caforio¹²⁹, V.M. Cairo^{39a,39b}, O. Cakir^{4a}, N. Calace⁵¹, P. Calafiura¹⁶, A. Calandri⁸⁷, G. Calderini⁸², P. Calfayan¹⁰¹, G. Callea^{39a,39b}, L.P. Caloba^{26a}, S. Calvente Lopez⁸⁴, D. Calvet³⁶, S. Calvet³⁶, T.P. Calvet⁸⁷, R. Camacho Toro³³, S. Camarda³², P. Camarri^{134a,134b}, D. Cameron¹²⁰, R. Caminal Armadans¹⁷⁰, C. Camincher⁵⁷, S. Campana³², M. Campanelli⁸⁰, A. Camplani^{93a,93b}, A. Campoverde¹⁴⁴, V. Canale^{105a,105b}, A. Canepa^{164a}, M. Cano Bret¹⁴¹, J. Cantero¹¹⁵, T. Cao⁴², M.D.M. Capeans Garrido³², I. Caprini^{28b}, M. Caprini^{28b}, M. Capua^{39a,39b}, R.M. Carbone³⁷, R. Cardarelli^{134a}, F. Cardillo⁵⁰, I. Carli¹³⁰, T. Carli³², G. Carlino^{105a}, L. Carminati^{93a,93b}, S. Caron¹⁰⁷, E. Carquin^{34b}, G.D. Carrillo-Montoya³², J.R. Carter³⁰, J. Carvalho^{127a,127c}, D. Casadei¹⁹, M.P. Casado^{13,i}, M. Casolino¹³, D.W. Casper¹⁶⁷, E. Castaneda-Miranda^{148a}, R. Castelijns¹⁰⁸, A. Castelli¹⁰⁸, V. Castillo Gimenez¹⁷¹, N.F. Castro^{127a,j}, A. Catinaccio³², J.R. Catmore¹²⁰, A. Cattai³², J. Caudron²³, V. Cavaliere¹⁷⁰, E. Cavallaro¹³, D. Cavalli^{93a}, M. Cavalli-Sforza¹³, V. Cavasinni^{125a,125b}, F. Ceradini^{135a,135b}, L. Cerda Alberich¹⁷¹, B.C. Cerio⁴⁷, A.S. Cerqueira^{26b}, A. Cerri¹⁵², L. Cerrito^{134a,134b}, F. Cerutti¹⁶, M. Cerv³², A. Cervelli¹⁸, S.A. Cetin^{20d}, A. Chafaq^{136a}, D. Chakraborty¹⁰⁹, S.K. Chan⁵⁸, Y.L. Chan^{62a}, P. Chang¹⁷⁰, J.D. Chapman³⁰, D.G. Charlton¹⁹, A. Chatterjee⁵¹, C.C. Chau¹⁶², C.A. Chavez Barajas¹⁵², S. Che¹¹², S. Cheatham^{168a,168c}, A. Chegwidden⁹², S. Chekanov⁶, S.V. Chekulaev^{164a}, G.A. Chelkov^{67,k}, M.A. Chelstowska⁹¹, C. Chen⁶⁶, H. Chen²⁷, K. Chen¹⁵¹, S. Chen^{35b}, S. Chen¹⁵⁸, X. Chen^{35c}, Y. Chen⁶⁹, H.C. Cheng⁹¹, H.J. Cheng^{35a}, Y. Cheng³³, A. Cheplakov⁶⁷, E. Cheremushkina¹³¹, R. Cherkaoui El Moursli^{136e}, V. Chernyatin^{27,*}, E. Cheu⁷, L. Chevalier¹³⁷, V. Chiarella⁴⁹, G. Chiarelli^{125a,125b}, G. Chiodini^{75a}, A.S. Chisholm³², A. Chitan^{28b}, M.V. Chizhov⁶⁷, K. Choi⁶³, A.R. Chomont³⁶, S. Chouridou⁹, B.K.B. Chow¹⁰¹, V. Christodoulou⁸⁰, D. Chromek-Burckhart³², J. Chudoba¹²⁸, A.J. Chuinard⁸⁹, J.J. Chwastowski⁴¹,

L. Chytka¹¹⁶, G. Ciapetti^{133a,133b}, A.K. Ciftci^{4a}, D. Cinca⁴⁵, V. Cindro⁷⁷, I.A. Cioara²³, C. Ciocca^{22a,22b}, A. Cicio¹⁶, F. Ciotto^{105a,105b}, Z.H. Citron¹⁷⁶, M. Citterio^{93a}, M. Ciubancan^{28b}, A. Clark⁵¹, B.L. Clark⁵⁸, M.R. Clark³⁷, P.J. Clark⁴⁸, R.N. Clarke¹⁶, C. Clement^{149a,149b}, Y. Coadou⁸⁷, M. Cobal^{168a,168c}, A. Coccaro⁵¹, J. Cochran⁶⁶, L. Colasurdo¹⁰⁷, B. Cole³⁷, A.P. Colijn¹⁰⁸, J. Collot⁵⁷, T. Colombo¹⁶⁷, G. Compostella¹⁰², P. Conde Muiño^{127a,127b}, E. Coniavitis⁵⁰, S.H. Connell^{148b}, I.A. Connelly⁷⁹, V. Consorti⁵⁰, S. Constantinescu^{28b}, G. Conti³², F. Conventi^{105a,l}, M. Cooke¹⁶, B.D. Cooper⁸⁰, A.M. Cooper-Sarkar¹²¹, K.J.R. Cormier¹⁶², T. Cornelissen¹⁷⁹, M. Corradi^{133a,133b}, F. Corriveau^{89,m}, A. Cortes-Gonzalez³², G. Cortiana¹⁰², G. Costa^{93a}, M.J. Costa¹⁷¹, D. Costanzo¹⁴², G. Cottin³⁰, G. Cowan⁷⁹, B.E. Cox⁸⁶, K. Cranmer¹¹¹, S.J. Crawley⁵⁵, G. Cree³¹, S. Crépé-Renaudin⁵⁷, F. Crescioli⁸², W.A. Cribbs^{149a,149b}, M. Crispin Ortuzar¹²¹, M. Cristinziani²³, V. Croft¹⁰⁷, G. Crosetti^{39a,39b}, A. Cueto⁸⁴, T. Cuhadar Donszelmann¹⁴², J. Cummings¹⁸⁰, M. Curatolo⁴⁹, J. Cúth⁸⁵, H. Czirr¹⁴⁴, P. Czodrowski³, G. D'amen^{22a,22b}, S. D'Auria⁵⁵, M. D'Onofrio⁷⁶, M.J. Da Cunha Sargedas De Sousa^{127a,127b}, C. Da Via⁸⁶, W. Dabrowski^{40a}, T. Dado^{147a}, T. Dai⁹¹, O. Dale¹⁵, F. Dallaire⁹⁶, C. Dallapiccola⁸⁸, M. Dam³⁸, J.R. Dandoy³³, N.P. Dang⁵⁰, A.C. Daniells¹⁹, N.S. Dann⁸⁶, M. Danninger¹⁷², M. Dano Hoffmann¹³⁷, V. Dao⁵⁰, G. Darbo^{52a}, S. Darmora⁸, J. Dassoulas³, A. Dattagupta¹¹⁷, W. Davey²³, C. David¹⁷³, T. Davidek¹³⁰, M. Davies¹⁵⁶, P. Davison⁸⁰, E. Dawe⁹⁰, I. Dawson¹⁴², K. De⁸, R. de Asmundis^{105a}, A. De Benedetti¹¹⁴, S. De Castro^{22a,22b}, S. De Cecco⁸², N. De Groot¹⁰⁷, P. de Jong¹⁰⁸, H. De la Torre⁹², F. De Lorenzi⁶⁶, A. De Maria⁵⁶, D. De Pedis^{133a}, A. De Salvo^{133a}, U. De Sanctis¹⁵², A. De Santo¹⁵², J.B. De Vivie De Regie¹¹⁸, W.J. Dearnaley⁷⁴, R. Debbe²⁷, C. Debenedetti¹³⁸, D.V. Dedovich⁶⁷, N. Dehghanian³, I. Deigaard¹⁰⁸, M. Del Gaudio^{39a,39b}, J. Del Peso⁸⁴, T. Del Prete^{125a,125b}, D. Delgove¹¹⁸, F. Deliot¹³⁷, C.M. Delitzsch⁵¹, A. Dell'Acqua³², L. Dell'Asta²⁴, M. Dell'Orso^{125a,125b}, M. Della Pietra^{105a,l}, D. della Volpe⁵¹, M. Delmastro⁵, P.A. Delsart⁵⁷, D.A. DeMarco¹⁶², S. Demers¹⁸⁰, M. Demichev⁶⁷, A. Demilly⁸², S.P. Denisov¹³¹, D. Denysiuk¹³⁷, D. Derendarz⁴¹, J.E. Derkaoui^{136d}, F. Derue⁸², P. Dervan⁷⁶, K. Desch²³, C. Deterre⁴⁴, K. Dette⁴⁵, P.O. Deviveiros³², A. Dewhurst¹³², S. Dhaliwal²⁵, A. Di Ciaccio^{134a,134b}, L. Di Ciaccio⁵, W.K. Di Clemente¹²³, C. Di Donato^{133a,133b}, A. Di Girolamo³², B. Di Girolamo³², B. Di Micco^{135a,135b}, R. Di Nardo³², A. Di Simone⁵⁰, R. Di Sipio¹⁶², D. Di Valentino³¹, C. Diaconu⁸⁷, M. Diamond¹⁶², F.A. Dias⁴⁸, M.A. Diaz^{34a}, E.B. Diehl⁹¹, J. Dietrich¹⁷, S. Díez Cornell⁴⁴, A. Dimitrievska¹⁴, J. Dingfelder²³, P. Dita^{28b}, S. Dita^{28b}, F. Dittus³², F. Djama⁸⁷, T. Djobava^{53b}, J.I. Djuvsland^{60a}, M.A.B. do Vale^{26c}, D. Dobos³², M. Dobre^{28b}, C. Doglioni⁸³, J. Dolejsi¹³⁰, Z. Dolezal¹³⁰, M. Donadelli^{26d}, S. Donati^{125a,125b}, P. Dondero^{122a,122b}, J. Donini³⁶, J. Dopke¹³², A. Doria^{105a}, M.T. Dova⁷³, A.T. Doyle⁵⁵, E. Drechsler⁵⁶, M. Dris¹⁰, Y. Du¹⁴⁰, J. Duarte-Campderros¹⁵⁶, E. Duchovni¹⁷⁶, G. Duckeck¹⁰¹, O.A. Ducu^{96,n}, D. Duda¹⁰⁸, A. Dudarev³², A. Chr. Dudder⁸⁵, E.M. Duffield¹⁶, L. Duflot¹¹⁸, M. Dührssen³², M. Dumancic¹⁷⁶, M. Dunford^{60a}, H. Duran Yildiz^{4a}, M. Düren⁵⁴, A. Durglishvili^{53b}, D. Duschinger⁴⁶, B. Dutta⁴⁴, M. Dyndal⁴⁴, C. Eckardt⁴⁴, K.M. Ecker¹⁰², R.C. Edgar⁹¹, N.C. Edwards⁴⁸, T. Eifert³², G. Eigen¹⁵, K. Einsweiler¹⁶, T. Ekelof¹⁶⁹, M. El Kacimi^{136c}, V. Ellajosyula⁸⁷, M. Ellert¹⁶⁹, S. Elles⁵, F. Ellinghaus¹⁷⁹, A.A. Elliot¹⁷³, N. Ellis³², J. Elmsheuser²⁷, M. Elsing³², D. Emelianov¹³², Y. Enari¹⁵⁸, O.C. Endner⁸⁵, J.S. Ennis¹⁷⁴, J. Erdmann⁴⁵, A. Ereditato¹⁸, G. Ernis¹⁷⁹, J. Ernst², M. Ernst²⁷, S. Errede¹⁷⁰, E. Ertel⁸⁵, M. Escalier¹¹⁸, H. Esch⁴⁵, C. Escobar¹²⁶, B. Esposito⁴⁹, A.I. Etienvre¹³⁷, E. Etzion¹⁵⁶, H. Evans⁶³, A. Ezhilov¹²⁴, M. Ezzi^{136e}, F. Fabbri^{22a,22b}, L. Fabbri^{22a,22b}, G. Facini³³, R.M. Fakhruddinov¹³¹, S. Falciano^{133a}, R.J. Falla⁸⁰, J. Faltova³², Y. Fang^{35a}, M. Fanti^{93a,93b}, A. Farbin⁸, A. Farilla^{135a}, C. Farina¹²⁶, E.M. Farina^{122a,122b}, T. Farooque¹³, S. Farrell¹⁶, S.M. Farrington¹⁷⁴, P. Farthouat³², F. Fassi^{136e}, P. Fassnacht³², D. Fassoulitis⁹, M. Fauci Giannelli⁷⁹, A. Favareto^{52a,52b}, W.J. Fawcett¹²¹, L. Fayard¹¹⁸, O.L. Fedin^{124,o}, W. Fedorko¹⁷², S. Feigl¹²⁰, L. Feligioni⁸⁷, C. Feng¹⁴⁰, E.J. Feng³², H. Feng⁹¹, A.B. Fenyuk¹³¹, L. Feremenga⁸, P. Fernandez Martinez¹⁷¹, S. Fernandez Perez¹³, J. Ferrando⁴⁴, A. Ferrari¹⁶⁹, P. Ferrari¹⁰⁸, R. Ferrari^{122a}, D.E. Ferreira de Lima^{60b}, A. Ferrer¹⁷¹, D. Ferrere⁵¹, C. Ferretti⁹¹, A. Ferretto Parodi^{52a,52b}, F. Fiedler⁸⁵, A. Filipčič⁷⁷, M. Filipuzzi⁴⁴, F. Filthaut¹⁰⁷, M. Fincke-Keeler¹⁷³, K.D. Finelli¹⁵³, M.C.N. Fiolhais^{127a,127c}, L. Fiorini¹⁷¹, A. Firan⁴², A. Fischer², C. Fischer¹³, J. Fischer¹⁷⁹, W.C. Fisher⁹², N. Flaschel⁴⁴, I. Fleck¹⁴⁴, P. Fleischmann⁹¹, G.T. Fletcher¹⁴², R.R.M. Fletcher¹²³, T. Flick¹⁷⁹, L.R. Flores Castillo^{62a}, M.J. Flowerdew¹⁰², G.T. Forcolin⁸⁶, A. Formica¹³⁷, A. Forti⁸⁶, A.G. Foster¹⁹, D. Fournier¹¹⁸, H. Fox⁷⁴, S. Fracchia¹³, P. Francavilla⁸², M. Franchini^{22a,22b}, D. Francis³², L. Franconi¹²⁰, M. Franklin⁵⁸, M. Frate¹⁶⁷, M. Fraternali^{122a,122b}, D. Freeborn⁸⁰, S.M. Fressard-Batraneanu³², F. Friedrich⁴⁶, D. Froidevaux³², J.A. Frost¹²¹, C. Fukunaga¹⁵⁹,

E. Fullana Torregrosa⁸⁵, T. Fusayasu¹⁰³, J. Fuster¹⁷¹, C. Gabaldon⁵⁷, O. Gabizon¹⁷⁹, A. Gabrielli^{22a,22b}, A. Gabrielli¹⁶, G.P. Gach^{40a}, S. Gadatsch³², S. Gadomski⁷⁹, G. Gagliardi^{52a,52b}, L.G. Gagnon⁹⁶, P. Gagnon⁶³, C. Galea¹⁰⁷, B. Galhardo^{127a,127c}, E.J. Gallas¹²¹, B.J. Gallop¹³², P. Gallus¹²⁹, G. Galster³⁸, K.K. Gan¹¹², J. Gao⁵⁹, Y. Gao⁴⁸, Y.S. Gao^{146,g}, F.M. Garay Walls⁴⁸, C. García¹⁷¹, J.E. García Navarro¹⁷¹, M. Garcia-Sciveres¹⁶, R.W. Gardner³³, N. Garelli¹⁴⁶, V. Garonne¹²⁰, A. Gascon Bravo⁴⁴, K. Gasnikova⁴⁴, C. Gatti⁴⁹, A. Gaudiello^{52a,52b}, G. Gaudio^{122a}, L. Gauthier⁹⁶, I.L. Gavrilenko⁹⁷, C. Gay¹⁷², G. Gaycken²³, E.N. Gazis¹⁰, Z. Gecse¹⁷², C.N.P. Gee¹³², Ch. Geich-Gimbel²³, M. Geisen⁸⁵, M.P. Geisler^{60a}, K. Gellerstedt^{149a,149b}, C. Gemme^{52a}, M.H. Genest⁵⁷, C. Geng^{59,p}, S. Gentile^{133a,133b}, C. Gentsos¹⁵⁷, S. George⁷⁹, D. Gerbaudo¹³, A. Gershon¹⁵⁶, S. Ghasemi¹⁴⁴, M. Ghneimat²³, B. Giacobbe^{22a}, S. Giagu^{133a,133b}, P. Giannetti^{125a,125b}, B. Gibbard²⁷, S.M. Gibson⁷⁹, M. Gignac¹⁷², M. Gilchriese¹⁶, T.P.S. Gillam³⁰, D. Gillberg³¹, G. Gilles¹⁷⁹, D.M. Gingrich^{3,d}, N. Giokaris⁹, M.P. Giordani^{168a,168c}, F.M. Giorgi^{22a}, F.M. Giorgi¹⁷, P.F. Giraud¹³⁷, P. Giromini⁵⁸, D. Giugni^{93a}, F. Giuli¹²¹, C. Giuliani¹⁰², M. Giulini^{60b}, B.K. Gjelsten¹²⁰, S. Gkaitatzis¹⁵⁷, I. Gkialas¹⁵⁷, E.L. Gkougkousis¹¹⁸, L.K. Gladilin¹⁰⁰, C. Glasman⁸⁴, J. Glatzer⁵⁰, P.C.F. Glaysher⁴⁸, A. Glazov⁴⁴, M. Goblirsch-Kolb²⁵, J. Godlewski⁴¹, S. Goldfarb⁹⁰, T. Golling⁵¹, D. Golubkov¹³¹, A. Gomes^{127a,127b,127d}, R. Gonçalo^{127a}, J. Goncalves Pinto Firmino Da Costa¹³⁷, G. Gonella⁵⁰, L. Gonella¹⁹, A. Gongadze⁶⁷, S. González de la Hoz¹⁷¹, G. Gonzalez Parra¹³, S. Gonzalez-Sevilla⁵¹, L. Goossens³², P.A. Gorbounov⁹⁸, H.A. Gordon²⁷, I. Gorelov¹⁰⁶, B. Gorini³², E. Gorini^{75a,75b}, A. Gorišek⁷⁷, E. Gornicki⁴¹, A.T. Goshaw⁴⁷, C. Gössling⁴⁵, M.I. Gostkin⁶⁷, C.R. Goudet¹¹⁸, D. Goujdami^{136c}, A.G. Goussiou¹³⁹, N. Govender^{148b,q}, E. Gozani¹⁵⁵, L. Graber⁵⁶, I. Grabowska-Bold^{40a}, P.O.J. Gradin⁵⁷, P. Grafström^{22a,22b}, J. Gramling⁵¹, E. Gramstad¹²⁰, S. Grancagnolo¹⁷, V. Gratchev¹²⁴, P.M. Gravila^{28e}, H.M. Gray³², E. Graziani^{135a}, Z.D. Greenwood^{81,r}, C. Greife²³, K. Gregersen⁸⁰, I.M. Gregor⁴⁴, P. Grenier¹⁴⁶, K. Grevtsov⁵, J. Griffiths⁸, A.A. Grillo¹³⁸, K. Grimm⁷⁴, S. Grinstein^{13,s}, Ph. Gris³⁶, J.-F. Grivaz¹¹⁸, S. Groh⁸⁵, J.P. Grohs⁴⁶, E. Gross¹⁷⁶, J. Grosse-Knetter⁵⁶, G.C. Grossi⁸¹, Z.J. Grout⁸⁰, L. Guan⁹¹, W. Guan¹⁷⁷, J. Guenther⁶⁴, F. Guescini⁵¹, D. Guest¹⁶⁷, O. Gueta¹⁵⁶, E. Guido^{52a,52b}, T. Guillemain⁵, S. Guindon², U. Gul⁵⁵, C. Gumpert³², J. Guo¹⁴¹, Y. Guo^{59,p}, R. Gupta⁴², S. Gupta¹²¹, G. Gustavino^{133a,133b}, P. Gutierrez¹¹⁴, N.G. Gutierrez Ortiz⁸⁰, C. Gutsche⁴⁶, C. Guyot¹³⁷, C. Gwenlan¹²¹, C.B. Gwilliam⁷⁶, A. Haas¹¹¹, C. Haber¹⁶, H.K. Hadavand⁸, N. Haddad^{136e}, A. Hadeef⁸⁷, S. Hageböck²³, M. Hagihara¹⁶⁵, Z. Hajduk⁴¹, H. Hakobyan^{181,*}, M. Haleem⁴⁴, J. Haley¹¹⁵, G. Halladjian⁹², G.D. Hallewell⁸⁷, K. Hamacher¹⁷⁹, P. Hamal¹¹⁶, K. Hamano¹⁷³, A. Hamilton^{148a}, G.N. Hamity¹⁴², P.G. Hamnett⁴⁴, L. Han⁵⁹, K. Hanagaki^{68,t}, K. Hanawa¹⁵⁸, M. Hance¹³⁸, B. Haney¹²³, P. Hanke^{60a}, R. Hanna¹³⁷, J.B. Hansen³⁸, J.D. Hansen³⁸, M.C. Hansen²³, P.H. Hansen³⁸, K. Hara¹⁶⁵, A.S. Hard¹⁷⁷, T. Harenberg¹⁷⁹, F. Hariri¹¹⁸, S. Harkusha⁹⁴, R.D. Harrington⁴⁸, P.F. Harrison¹⁷⁴, F. Hartjes¹⁰⁸, N.M. Hartmann¹⁰¹, M. Hasegawa⁶⁹, Y. Hasegawa¹⁴³, A. Hasib¹¹⁴, S. Hassani¹³⁷, S. Haug¹⁸, R. Hauser⁹², L. Hauswald⁴⁶, M. Havranek¹²⁸, C.M. Hawkes¹⁹, R.J. Hawkings³², D. Hayakawa¹⁶⁰, D. Hayden⁹², C.P. Hays¹²¹, J.M. Hays⁷⁸, H.S. Hayward⁷⁶, S.J. Haywood¹³², S.J. Head¹⁹, T. Heck⁸⁵, V. Hedberg⁸³, L. Heelan⁸, S. Heim¹²³, T. Heim¹⁶, B. Heinemann¹⁶, J.J. Heinrich¹⁰¹, L. Heinrich¹¹¹, C. Heinz⁵⁴, J. Hejbal¹²⁸, L. Helary³², S. Hellman^{149a,149b}, C. Helsen³², J. Henderson¹²¹, R.C.W. Henderson⁷⁴, Y. Heng¹⁷⁷, S. Henkelmann¹⁷², A.M. Henriques Correia³², S. Henrot-Versille¹¹⁸, G.H. Herbert¹⁷, H. Herde²⁵, V. Herget¹⁷⁸, Y. Hernández Jiménez¹⁷¹, G. Herten⁵⁰, R. Hertenberger¹⁰¹, L. Hervas³², G.G. Hesketh⁸⁰, N.P. Hessey¹⁰⁸, J.W. Hetherly⁴², R. Hickling⁷⁸, E. Higón-Rodríguez¹⁷¹, E. Hill¹⁷³, J.C. Hill³⁰, K.H. Hiller⁴⁴, S.J. Hillier¹⁹, I. Hinchliffe¹⁶, E. Hines¹²³, R.R. Hinman¹⁶, M. Hirose⁵⁰, D. Hirschbuehl¹⁷⁹, J. Hobbs¹⁵¹, N. Hod^{164a}, M.C. Hodgkinson¹⁴², P. Hodgson¹⁴², A. Hoecker³², M.R. Hoefkamp¹⁰⁶, F. Hoenig¹⁰¹, D. Hohn²³, T.R. Holmes¹⁶, M. Homann⁴⁵, T. Honda⁶⁸, T.M. Hong¹²⁶, B.H. Hooberman¹⁷⁰, W.H. Hopkins¹¹⁷, Y. Horii¹⁰⁴, A.J. Horton¹⁴⁵, J.-Y. Hostachy⁵⁷, S. Hou¹⁵⁴, A. Hoummada^{136a}, J. Howarth⁴⁴, J. Hoya⁷³, M. Hrabovsky¹¹⁶, I. Hristova¹⁷, J. Hrivnac¹¹⁸, T. Hryn'ova⁵, A. Hrynevich⁹⁵, C. Hsu^{148c}, P.J. Hsu^{154,u}, S.-C. Hsu¹³⁹, Q. Hu⁵⁹, S. Hu¹⁴¹, Y. Huang⁴⁴, Z. Hubacek¹²⁹, F. Hubaut⁸⁷, F. Huegging²³, T.B. Huffman¹²¹, E.W. Hughes³⁷, G. Hughes⁷⁴, M. Huhtinen³², P. Huo¹⁵¹, N. Huseynov^{67,b}, J. Huston⁹², J. Huth⁵⁸, G. Iacobucci⁵¹, G. Iakovidis²⁷, I. Ibragimov¹⁴⁴, L. Iconomidou-Fayard¹¹⁸, E. Ideal¹⁸⁰, Z. Idrissi^{136e}, P. Iengo³², O. Igonkina^{108,v}, T. Iizawa¹⁷⁵, Y. Ikegami⁶⁸, M. Ikeno⁶⁸, Y. Ilchenko^{11,w}, D. Iliadis¹⁵⁷, N. Ilic¹⁴⁶, T. Ince¹⁰², G. Introzzi^{122a,122b}, P. Ioannou^{9,*}, M. Iodice^{135a}, K. Iordanidou³⁷, V. Ippolito⁵⁸, N. Ishijima¹¹⁹, M. Ishino¹⁵⁸, M. Ishitsuka¹⁶⁰, R. Ishmukhametov¹¹², C. Issever¹²¹,

S. Istin^{20a}, F. Ito¹⁶⁵, J.M. Iturbe Ponce⁸⁶, R. Iuppa^{163a,163b}, W. Iwanski⁶⁴, H. Iwasaki⁶⁸, J.M. Izen⁴³, V. Izzo^{105a}, S. Jabbar³, B. Jackson¹²³, P. Jackson¹, V. Jain², K.B. Jakobi⁸⁵, K. Jakobs⁵⁰, S. Jakobsen³², T. Jakoubek¹²⁸, D.O. Jamin¹¹⁵, D.K. Jana⁸¹, R. Jansky⁶⁴, J. Janssen²³, M. Janus⁵⁶, G. Jarlskog⁸³, N. Javadov^{67,b}, T. Javůrek⁵⁰, F. Jeanneau¹³⁷, L. Jeanty¹⁶, G.-Y. Jeng¹⁵³, D. Jennens⁹⁰, P. Jenni^{50,x}, C. Jeske¹⁷⁴, S. Jézéquel⁵, H. Ji¹⁷⁷, J. Jia¹⁵¹, H. Jiang⁶⁶, Y. Jiang⁵⁹, S. Jiggins⁸⁰, J. Jimenez Pena¹⁷¹, S. Jin^{35a}, A. Jinaru^{28b}, O. Jinnouchi¹⁶⁰, H. Jivan^{148c}, P. Johansson¹⁴², K.A. Johns⁷, W.J. Johnson¹³⁹, K. Jon-And^{149a,149b}, G. Jones¹⁷⁴, R.W.L. Jones⁷⁴, S. Jones⁷, T.J. Jones⁷⁶, J. Jongmanns^{60a}, P.M. Jorge^{127a,127b}, J. Jovicevic^{164a}, X. Ju¹⁷⁷, A. Juste Rozas^{13,s}, M.K. Köhler¹⁷⁶, A. Kaczmarzka⁴¹, M. Kado¹¹⁸, H. Kagan¹¹², M. Kagan¹⁴⁶, S.J. Kahn⁸⁷, T. Kaji¹⁷⁵, E. Kajomovitz⁴⁷, C.W. Kalderon¹²¹, A. Kaluza⁸⁵, S. Kama⁴², A. Kamenshchikov¹³¹, N. Kanaya¹⁵⁸, S. Kaneti³⁰, L. Kanjir⁷⁷, V.A. Kantserov⁹⁹, J. Kanzaki⁶⁸, B. Kaplan¹¹¹, L.S. Kaplan¹⁷⁷, A. Kapliy³³, D. Kar^{148c}, K. Karakostas¹⁰, A. Karamaoun³, N. Karastathis¹⁰, M.J. Kareem⁵⁶, E. Karentzos¹⁰, M. Karnevskiy⁸⁵, S.N. Karpov⁶⁷, Z.M. Karpova⁶⁷, K. Karthik¹¹¹, V. Kartvelishvili⁷⁴, A.N. Karyukhin¹³¹, K. Kasahara¹⁶⁵, L. Kashif¹⁷⁷, R.D. Kass¹¹², A. Kastanas¹⁵, Y. Kataoka¹⁵⁸, C. Kato¹⁵⁸, A. Katre⁵¹, J. Katzy⁴⁴, K. Kawade¹⁰⁴, K. Kawagoe⁷², T. Kawamoto¹⁵⁸, G. Kawamura⁵⁶, V.F. Kazanin^{110,c}, R. Keeler¹⁷³, R. Kehoe⁴², J.S. Keller⁴⁴, J.J. Kempster⁷⁹, H. Keoshkerian¹⁶², O. Kepka¹²⁸, B.P. Kerševan⁷⁷, S. Kersten¹⁷⁹, R.A. Keyes⁸⁹, M. Khader¹⁷⁰, F. Khalil-zada¹², A. Khanov¹¹⁵, A.G. Kharlamov^{110,c}, T. Kharlamova¹¹⁰, T.J. Khoo⁵¹, V. Khovanskii⁹⁸, E. Khramov⁶⁷, J. Khubua^{53b,y}, S. Kido⁶⁹, C.R. Kilby⁷⁹, H.Y. Kim⁸, S.H. Kim¹⁶⁵, Y.K. Kim³³, N. Kimura¹⁵⁷, O.M. Kind¹⁷, B.T. King⁷⁶, M. King¹⁷¹, J. Kirk¹³², A.E. Kiryunin¹⁰², T. Kishimoto¹⁵⁸, D. Kisielewska^{40a}, F. Kiss⁵⁰, K. Kiuchi¹⁶⁵, O. Kivernyk¹³⁷, E. Kladiva^{147b}, M.H. Klein³⁷, M. Klein⁷⁶, U. Klein⁷⁶, K. Kleinknecht⁸⁵, P. Klimek¹⁰⁹, A. Klimentov²⁷, R. Klingenberg⁴⁵, J.A. Klinger¹⁴², T. Klioutchnikova³², E.-E. Kluge^{60a}, P. Kluit¹⁰⁸, S. Kluth¹⁰², J. Knapik⁴¹, E. Kneringer⁶⁴, E.B.F.G. Knoop⁸⁷, A. Knue⁵⁵, A. Kobayashi¹⁵⁸, D. Kobayashi¹⁶⁰, T. Kobayashi¹⁵⁸, M. Kobel⁴⁶, M. Kocian¹⁴⁶, P. Kodys¹³⁰, N.M. Koehler¹⁰², T. Koffas³¹, E. Koffeman¹⁰⁸, T. Koi¹⁴⁶, H. Kolanoski¹⁷, M. Kolb^{60b}, I. Koletsou⁵, A.A. Komar^{97,*}, Y. Komori¹⁵⁸, T. Kondo⁶⁸, N. Kondrashova⁴⁴, K. Köneke⁵⁰, A.C. König¹⁰⁷, T. Kono^{68,z}, R. Konoplich^{111,aa}, N. Konstantinidis⁸⁰, R. Kopeliansky⁶³, S. Koperny^{40a}, L. Köpke⁸⁵, A.K. Kopp⁵⁰, K. Korcyl⁴¹, K. Kordas¹⁵⁷, A. Korn⁸⁰, A.A. Korol^{110,c}, I. Korolkov¹³, E.V. Korolkova¹⁴², O. Kortner¹⁰², S. Kortner¹⁰², T. Kosek¹³⁰, V.V. Kostyukhin²³, A. Kotwal⁴⁷, A. Kourkouveli-Charalampidi^{122a,122b}, C. Kourkouvelis⁹, V. Kouskoura²⁷, A.B. Kowalewska⁴¹, R. Kowalewski¹⁷³, T.Z. Kowalski^{40a}, C. Kozakai¹⁵⁸, W. Kozanecki¹³⁷, A.S. Kozhin¹³¹, V.A. Kramarenko¹⁰⁰, G. Kramberger⁷⁷, D. Krasnopevtsev⁹⁹, M.W. Krasny⁸², A. Krasznahorkay³², A. Kravchenko²⁷, M. Kretz^{60c}, J. Kretzschmar⁷⁶, K. Kreutzfeldt⁵⁴, P. Krieger¹⁶², K. Krizka³³, K. Kroeninger⁴⁵, H. Kroha¹⁰², J. Kroll¹²³, J. Kroseberg²³, J. Krstic¹⁴, U. Kruchonak⁶⁷, H. Krüger²³, N. Krumnack⁶⁶, M.C. Kruse⁴⁷, M. Kruskal²⁴, T. Kubota⁹⁰, H. Kucuk⁸⁰, S. Kuday^{4b}, J.T. Kuechler¹⁷⁹, S. Kuehn⁵⁰, A. Kugel^{60c}, F. Kuger¹⁷⁸, A. Kuhl¹³⁸, T. Kuhl⁴⁴, V. Kukhtin⁶⁷, R. Kukla¹³⁷, Y. Kulchitsky⁹⁴, S. Kuleshov^{34b}, M. Kuna^{133a,133b}, T. Kunigo⁷⁰, A. Kupco¹²⁸, H. Kurashige⁶⁹, Y.A. Kurochkin⁹⁴, V. Kus¹²⁸, E.S. Kuwertz¹⁷³, M. Kuze¹⁶⁰, J. Kvita¹¹⁶, T. Kwan¹⁷³, D. Kyriazopoulos¹⁴², A. La Rosa¹⁰², J.L. La Rosa Navarro^{26d}, L. La Rotonda^{39a,39b}, C. Lacasta¹⁷¹, F. Lacava^{133a,133b}, J. Lacey³¹, H. Lacker¹⁷, D. Lacour⁸², V.R. Lacuesta¹⁷¹, E. Ladygin⁶⁷, R. Lafaye⁵, B. Laforge⁸², T. Lagouri¹⁸⁰, S. Lai⁵⁶, S. Lammers⁶³, W. Lampl⁷, E. Lançon¹³⁷, U. Landgraf⁵⁰, M.P.J. Landon⁷⁸, M.C. Lanfermann⁵¹, V.S. Lang^{60a}, J.C. Lange¹³, A.J. Lankford¹⁶⁷, F. Lanni²⁷, K. Lantzsch²³, A. Lanza^{122a}, S. Laplace⁸², C. Lapoire³², J.F. Laporte¹³⁷, T. Lari^{93a}, F. Lasagni Manghi^{22a,22b}, M. Lassnig³², P. Laurelli⁴⁹, W. Lavrijsen¹⁶, A.T. Law¹³⁸, P. Laycock⁷⁶, T. Lazovich⁵⁸, M. Lazzaroni^{93a,93b}, B. Le⁹⁰, O. Le Dortz⁸², E. Le Guirriec⁸⁷, E.P. Le Quilleuc¹³⁷, M. LeBlanc¹⁷³, T. LeCompte⁶, F. Ledroit-Guillon⁵⁷, C.A. Lee²⁷, S.C. Lee¹⁵⁴, L. Lee¹, B. Lefebvre⁸⁹, G. Lefebvre⁸², M. Lefebvre¹⁷³, F. Legger¹⁰¹, C. Leggett¹⁶, A. Lehan⁷⁶, G. Lehmann Miotto³², X. Lei⁷, W.A. Leight³¹, A.G. Leister¹⁸⁰, M.A.L. Leite^{26d}, R. Leitner¹³⁰, D. Lellouch¹⁷⁶, B. Lemmer⁵⁶, K.J.C. Leney⁸⁰, T. Lenz²³, B. Lenzi³², R. Leone⁷, S. Leone^{125a,125b}, C. Leonidopoulos⁴⁸, S. Leontsinis¹⁰, G. Lerner¹⁵², C. Leroy⁹⁶, A.A.J. Lesage¹³⁷, C.G. Lester³⁰, M. Levchenko¹²⁴, J. Levêque⁵, D. Levin⁹¹, L.J. Levinson¹⁷⁶, M. Levy¹⁹, D. Lewis⁷⁸, A.M. Leyko²³, M. Leyton⁴³, B. Li^{59,p}, C. Li⁵⁹, H. Li¹⁵¹, H.L. Li³³, L. Li⁴⁷, L. Li¹⁴¹, Q. Li^{35a}, S. Li⁴⁷, X. Li⁸⁶, Y. Li¹⁴⁴, Z. Liang^{35a}, B. Liberti^{134a}, A. Liblong¹⁶², P. Lichard³², K. Lie¹⁷⁰, J. Liebal²³, W. Liebig¹⁵, A. Limosani¹⁵³, S.C. Lin^{154,ab}, T.H. Lin⁸⁵, B.E. Lindquist¹⁵¹, A.E. Lioni⁵¹, E. Lipeles¹²³, A. Lipniacka¹⁵, M. Lisovsky^{60b}, T.M. Liss¹⁷⁰, A. Lister¹⁷², A.M. Litke¹³⁸, B. Liu^{154,ac},

D. Liu¹⁵⁴, H. Liu⁹¹, H. Liu²⁷, J. Liu⁸⁷, J.B. Liu⁵⁹, K. Liu⁸⁷, L. Liu¹⁷⁰, M. Liu⁴⁷, M. Liu⁵⁹, Y.L. Liu⁵⁹, Y. Liu⁵⁹, M. Livan^{122a,122b}, A. Lleres⁵⁷, J. Llorente Merino^{35a}, S.L. Lloyd⁷⁸, F. Lo Sterzo¹⁵⁴, E.M. Lobodzinska⁴⁴, P. Loch⁷, W.S. Lockman¹³⁸, F.K. Loebinger⁸⁶, A.E. Loevschall-Jensen³⁸, K.M. Loew²⁵, A. Loginov^{180,*}, T. Lohse¹⁷, K. Lohwasser⁴⁴, M. Lokajicek¹²⁸, B.A. Long²⁴, J.D. Long¹⁷⁰, R.E. Long⁷⁴, L. Longo^{75a,75b}, K.A. Looper¹¹², J.A. López^{34b}, D. Lopez Mateos⁵⁸, B. Lopez Paredes¹⁴², I. Lopez Paz¹³, A. Lopez Solis⁸², J. Lorenz¹⁰¹, N. Lorenzo Martinez⁶³, M. Losada²¹, P.J. Lösel¹⁰¹, X. Lou^{35a}, A. Lounis¹¹⁸, J. Love⁶, P.A. Love⁷⁴, H. Lu^{62a}, N. Lu⁹¹, H.J. Lubatti¹³⁹, C. Luci^{133a,133b}, A. Lucotte⁵⁷, C. Luedtke⁵⁰, F. Luehring⁶³, W. Lukas⁶⁴, L. Luminari^{133a}, O. Lundberg^{149a,149b}, B. Lund-Jensen¹⁵⁰, P.M. Luzi⁸², D. Lynn²⁷, R. Lysak¹²⁸, E. Lytken⁸³, V. Lyubushkin⁶⁷, H. Ma²⁷, L.L. Ma¹⁴⁰, Y. Ma¹⁴⁰, G. Maccarrone⁴⁹, A. Macchiolo¹⁰², C.M. Macdonald¹⁴², B. Maček⁷⁷, J. Machado Miguens^{123,127b}, D. Madaffari⁸⁷, R. Madar³⁶, H.J. Maddocks¹⁶⁹, W.F. Mader⁴⁶, A. Madsen⁴⁴, J. Maeda⁶⁹, S. Maeland¹⁵, T. Maeno²⁷, A. Maevskiy¹⁰⁰, E. Magradze⁵⁶, J. Mahlstedt¹⁰⁸, C. Maiani¹¹⁸, C. Maidantchik^{26a}, A.A. Maier¹⁰², T. Maier¹⁰¹, A. Maio^{127a,127b,127d}, S. Majewski¹¹⁷, Y. Makida⁶⁸, N. Makovec¹¹⁸, B. Malaescu⁸², Pa. Malecki⁴¹, V.P. Maleev¹²⁴, F. Malek⁵⁷, U. Mallik⁶⁵, D. Malon⁶, C. Malone¹⁴⁶, C. Malone³⁰, S. Maltezos¹⁰, S. Malyukov³², J. Mamuzic¹⁷¹, G. Mancini⁴⁹, L. Mandelli^{93a}, I. Mandić⁷⁷, J. Maneira^{127a,127b}, L. Manhaes de Andrade Filho^{26b}, J. Manjarres Ramos^{164b}, A. Mann¹⁰¹, A. Manousos³², B. Mansoulie¹³⁷, J.D. Mansour^{35a}, R. Mantifel⁸⁹, M. Mantoani⁵⁶, S. Manzoni^{93a,93b}, L. Mapelli³², G. Marceca²⁹, L. March⁵¹, G. Marchiori⁸², M. Marcisovsky¹²⁸, M. Marjanovic¹⁴, D.E. Marley⁹¹, F. Marroquim^{26a}, S.P. Marsden⁸⁶, Z. Marshall¹⁶, S. Marti-Garcia¹⁷¹, B. Martin⁹², T.A. Martin¹⁷⁴, V.J. Martin⁴⁸, B. Martin dit Latour¹⁵, M. Martinez^{13,s}, V.I. Martinez Outschoorn¹⁷⁰, S. Martin-Haugh¹³², V.S. Martoiu^{28b}, A.C. Martyniuk⁸⁰, A. Marzin³², L. Masetti⁸⁵, T. Mashimo¹⁵⁸, R. Mashinistov⁹⁷, J. Masik⁸⁶, A.L. Maslennikov^{110,c}, I. Massa^{22a,22b}, L. Massa^{22a,22b}, P. Mastrandrea⁵, A. Mastroberardino^{39a,39b}, T. Masubuchi¹⁵⁸, P. Mättig¹⁷⁹, J. Mattmann⁸⁵, J. Maurer^{28b}, S.J. Maxfield⁷⁶, D.A. Maximov^{110,c}, R. Mazini¹⁵⁴, S.M. Mazza^{93a,93b}, N.C. Mc Fadden¹⁰⁶, G. Mc Goldrick¹⁶², S.P. Mc Kee⁹¹, A. McCarn⁹¹, R.L. McCarthy¹⁵¹, T.G. McCarthy¹⁰², L.I. McClymont⁸⁰, E.F. McDonald⁹⁰, J.A. Mcfayden⁸⁰, G. Mchedlidze⁵⁶, S.J. McMahon¹³², R.A. McPherson^{173,m}, M. Medinnis⁴⁴, S. Meehan¹³⁹, S. Mehlhase¹⁰¹, A. Mehta⁷⁶, K. Meier^{60a}, C. Meineck¹⁰¹, B. Meirose⁴³, D. Melini¹⁷¹, B.R. Mellado Garcia^{148c}, M. Melo^{147a}, F. Meloni¹⁸, A. Mengarelli^{22a,22b}, S. Menke¹⁰², E. Meoni¹⁶⁶, S. Mergelmeyer¹⁷, P. Mermod⁵¹, L. Merola^{105a,105b}, C. Meroni^{93a}, F.S. Merritt³³, A. Messina^{133a,133b}, J. Metcalfe⁶, A.S. Mete¹⁶⁷, C. Meyer⁸⁵, C. Meyer¹²³, J-P. Meyer¹³⁷, J. Meyer¹⁰⁸, H. Meyer Zu Theenhausen^{60a}, F. Miano¹⁵², R.P. Middleton¹³², S. Miglioranza^{52a,52b}, L. Mijović⁴⁸, G. Mikenberg¹⁷⁶, M. Mikestikova¹²⁸, M. Mikuž⁷⁷, M. Milesi⁹⁰, A. Milic⁶⁴, D.W. Miller³³, C. Mills⁴⁸, A. Milov¹⁷⁶, D.A. Milstead^{149a,149b}, A.A. Minaenko¹³¹, Y. Minami¹⁵⁸, I.A. Minashvili⁶⁷, A.I. Mincer¹¹¹, B. Mindur^{40a}, M. Mineev⁶⁷, Y. Minegishi¹⁵⁸, Y. Ming¹⁷⁷, L.M. Mir¹³, K.P. Mistry¹²³, T. Mitani¹⁷⁵, J. Mitrevski¹⁰¹, V.A. Mitsou¹⁷¹, A. Miucci¹⁸, P.S. Miyagawa¹⁴², J.U. Mjörnmark⁸³, M. Mlynarikova¹³⁰, T. Moa^{149a,149b}, K. Mochizuki⁹⁶, S. Mohapatra³⁷, S. Molander^{149a,149b}, R. Moles-Valls²³, R. Monden⁷⁰, M.C. Mondragon⁹², K. Mönig⁴⁴, J. Monk³⁸, E. Monnier⁸⁷, A. Montalbano¹⁵¹, J. Montejo Berlingen³², F. Monticelli⁷³, S. Monzani^{93a,93b}, R.W. Moore³, N. Morange¹¹⁸, D. Moreno²¹, M. Moreno Llácer⁵⁶, P. Morettini^{52a}, S. Morgenstern³², D. Mori¹⁴⁵, T. Mori¹⁵⁸, M. Morii⁵⁸, M. Morinaga¹⁵⁸, V. Morisbak¹²⁰, S. Moritz⁸⁵, A.K. Morley¹⁵³, G. Mornacchi³², J.D. Morris⁷⁸, S.S. Mortensen³⁸, L. Morvaj¹⁵¹, M. Mosidze^{53b}, J. Moss^{146,ad}, K. Motohashi¹⁶⁰, R. Mount¹⁴⁶, E. Mountricha²⁷, E.J.W. Moyse⁸⁸, S. Muanza⁸⁷, R.D. Mudd¹⁹, F. Mueller¹⁰², J. Mueller¹²⁶, R.S.P. Mueller¹⁰¹, T. Mueller³⁰, D. Muenstermann⁷⁴, P. Mullen⁵⁵, G.A. Mullier¹⁸, F.J. Munoz Sanchez⁸⁶, J.A. Murillo Quijada¹⁹, W.J. Murray^{174,132}, H. Musheghyan⁵⁶, M. Muškinja⁷⁷, A.G. Myagkov^{131,ae}, M. Myska¹²⁹, B.P. Nachman¹⁴⁶, O. Nackenhorst⁵¹, K. Nagai¹²¹, R. Nagai^{68,z}, K. Nagano⁶⁸, Y. Nagasaka⁶¹, K. Nagata¹⁶⁵, M. Nagel⁵⁰, E. Nagy⁸⁷, A.M. Nairz³², Y. Nakahama¹⁰⁴, K. Nakamura⁶⁸, T. Nakamura¹⁵⁸, I. Nakano¹¹³, H. Namasivayam⁴³, R.F. Naranjo Garcia⁴⁴, R. Narayan¹¹, D.I. Narrias Villar^{60a}, I. Naryshkin¹²⁴, T. Naumann⁴⁴, G. Navarro²¹, R. Nayyar⁷, H.A. Neal⁹¹, P.Yu. Nechaeva⁹⁷, T.J. Neep⁸⁶, A. Negri^{122a,122b}, M. Negrini^{22a}, S. Nektarijevic¹⁰⁷, C. Nellist¹¹⁸, A. Nelson¹⁶⁷, S. Nemecek¹²⁸, P. Nemethy¹¹¹, A.A. Nepomuceno^{26a}, M. Nessi^{32,af}, M.S. Neubauer¹⁷⁰, M. Neumann¹⁷⁹, R.M. Neves¹¹¹, P. Nevski²⁷, P.R. Newman¹⁹, D.H. Nguyen⁶, T. Nguyen Manh⁹⁶, R.B. Nickerson¹²¹, R. Nicolaïdou¹³⁷, J. Nielsen¹³⁸, A. Nikiforov¹⁷, V. Nikolaenko^{131,ae}, I. Nikolic-Audit⁸², K. Nikolopoulos¹⁹, J.K. Nilsen¹²⁰, P. Nilsson²⁷,

Y. Ninomiya¹⁵⁸, A. Nisati^{133a}, R. Nisius¹⁰², T. Nobe¹⁵⁸, M. Nomachi¹¹⁹, I. Nomidis³¹, T. Nooney⁷⁸, S. Norberg¹¹⁴, M. Nordberg³², N. Norjoharuddeen¹²¹, O. Novgorodova⁴⁶, S. Nowak¹⁰², M. Nozaki⁶⁸, L. Nozka¹¹⁶, K. Ntekas¹⁶⁷, E. Nurse⁸⁰, F. Nuti⁹⁰, F. O'grady⁷, D.C. O'Neil¹⁴⁵, A.A. O'Rourke⁴⁴, V. O'Shea⁵⁵, F.G. Oakham^{31,d}, H. Oberlack¹⁰², T. Obermann²³, J. Ocariz⁸², A. Ochi⁶⁹, I. Ochoa³⁷, J.P. Ochoa-Ricoux^{34a}, S. Oda⁷², S. Odaka⁶⁸, H. Ogren⁶³, A. Oh⁸⁶, S.H. Oh⁴⁷, C.C. Ohm¹⁶, H. Ohman¹⁶⁹, H. Oide³², H. Okawa¹⁶⁵, Y. Okumura¹⁵⁸, T. Okuyama⁶⁸, A. Olariu^{28b}, L.F. Oleiro Seabra^{127a}, S.A. Olivares Pino⁴⁸, D. Oliveira Damazio²⁷, A. Olszewski⁴¹, J. Olszowska⁴¹, A. Onofre^{127a,127e}, K. Onogi¹⁰⁴, P.U.E. Onyisi^{11,w}, M.J. Oreglia³³, Y. Oren¹⁵⁶, D. Orestano^{135a,135b}, N. Orlando^{62b}, R.S. Orr¹⁶², B. Osculati^{52a,52b,*}, R. Ospanov⁸⁶, G. Otero y Garzon²⁹, H. Otono⁷², M. Ouchrif^{136d}, F. Ould-Saada¹²⁰, A. Ouraou¹³⁷, K.P. Oussoren¹⁰⁸, Q. Ouyang^{35a}, M. Owen⁵⁵, R.E. Owen¹⁹, V.E. Ozcan^{20a}, N. Ozturk⁸, K. Pachal¹⁴⁵, A. Pacheco Pages¹³, L. Pacheco Rodriguez¹³⁷, C. Padilla Aranda¹³, M. Pagáčová⁵⁰, S. Pagan Griso¹⁶, M. Paganini¹⁸⁰, F. Paige²⁷, P. Pais⁸⁸, K. Pajchel¹²⁰, G. Palacino^{164b}, S. Palazzo^{39a,39b}, S. Palestini³², M. Palka^{40b}, D. Pallin³⁶, E.St. Panagiotopoulou¹⁰, C.E. Pandini⁸², J.G. Panduro Vazquez⁷⁹, P. Pani^{149a,149b}, S. Panitkin²⁷, D. Pantea^{28b}, L. Paolozzi⁵¹, Th.D. Papadopoulos¹⁰, K. Papageorgiou¹⁵⁷, A. Paramonov⁶, D. Paredes Hernandez¹⁸⁰, A.J. Parker⁷⁴, M.A. Parker³⁰, K.A. Parker¹⁴², F. Parodi^{52a,52b}, J.A. Parsons³⁷, U. Parzefall⁵⁰, V.R. Pascuzzi¹⁶², E. Pasqualucci^{133a}, S. Passaggio^{52a}, Fr. Pastore⁷⁹, G. Pásztor^{31,ag}, S. Pataria¹⁷⁹, J.R. Pater⁸⁶, T. Pauly³², J. Pearce¹⁷³, B. Pearson¹¹⁴, L.E. Pedersen³⁸, M. Pedersen¹²⁰, S. Pedraza Lopez¹⁷¹, R. Pedro^{127a,127b}, S.V. Peleganchuk^{110,c}, O. Penc¹²⁸, C. Peng^{35a}, H. Peng⁵⁹, J. Penwell⁶³, B.S. Peralva^{26b}, M.M. Perego¹³⁷, D.V. Perepelitsa²⁷, E. Perez Codina^{164a}, L. Perini^{93a,93b}, H. Pernegger³², S. Perrella^{105a,105b}, R. Peschke⁴⁴, V.D. Peshekhonov⁶⁷, K. Peters⁴⁴, R.F.Y. Peters⁸⁶, B.A. Petersen³², T.C. Petersen³⁸, E. Petit⁵⁷, A. Petridis¹, C. Petridou¹⁵⁷, P. Petroff¹¹⁸, E. Petrolo^{133a}, M. Petrov¹²¹, F. Petrucci^{135a,135b}, N.E. Pettersson⁸⁸, A. Peyaud¹³⁷, R. Pezoa^{34b}, P.W. Phillips¹³², G. Piacquadio^{146,ah}, E. Pianori¹⁷⁴, A. Picazio⁸⁸, E. Piccaro⁷⁸, M. Piccinini^{22a,22b}, M.A. Pickering¹²¹, R. Piegaia²⁹, J.E. Pilcher³³, A.D. Pilkington⁸⁶, A.W.J. Pin⁸⁶, M. Pinamonti^{168a,168c,ai}, J.L. Pinfold³, A. Pingel³⁸, S. Pires⁸², H. Pirumov⁴⁴, M. Pitt¹⁷⁶, L. Plazak^{147a}, M.-A. Pleier²⁷, V. Pleskot⁸⁵, E. Plotnikova⁶⁷, P. Plucinski⁹², D. Pluth⁶⁶, R. Poettgen^{149a,149b}, L. Poggioli¹¹⁸, D. Pohl²³, G. Polesello^{122a}, A. Poley⁴⁴, A. Policicchio^{39a,39b}, R. Polifka¹⁶², A. Polini^{22a}, C.S. Pollard⁵⁵, V. Polychronakos²⁷, K. Pommès³², L. Pontecorvo^{133a}, B.G. Pope⁹², G.A. Popeneciu^{28c}, A. Poppleton³², S. Pospisil¹²⁹, K. Potamianos¹⁶, I.N. Potrap⁶⁷, C.J. Potter³⁰, C.T. Potter¹¹⁷, G. Poulard³², J. Poveda³², V. Pozdnyakov⁶⁷, M.E. Pozo Astigarraga³², P. Pralavorio⁸⁷, A. Pranko¹⁶, S. Prell⁶⁶, D. Price⁸⁶, L.E. Price⁶, M. Primavera^{75a}, S. Prince⁸⁹, K. Prokofiev^{62c}, F. Prokoshin^{34b}, S. Protopopescu²⁷, J. Proudfoot⁶, M. Przybycien^{40a}, D. Puddu^{135a,135b}, M. Purohit^{27,qj}, P. Puzo¹¹⁸, J. Qian⁹¹, G. Qin⁵⁵, Y. Qin⁸⁶, A. Quadt⁵⁶, W.B. Quayle^{168a,168b}, M. Queitsch-Maitland⁸⁶, D. Quilty⁵⁵, S. Raddum¹²⁰, V. Radeka²⁷, V. Radescu¹²¹, S.K. Radhakrishnan¹⁵¹, P. Radloff¹¹⁷, P. Rados⁹⁰, F. Ragusa^{93a,93b}, G. Rahal¹⁸², J.A. Raine⁸⁶, S. Rajagopalan²⁷, M. Rammensee³², C. Rangel-Smith¹⁶⁹, M.G. Ratti^{93a,93b}, F. Rauscher¹⁰¹, S. Rave⁸⁵, T. Ravenscroft⁵⁵, I. Ravinovich¹⁷⁶, M. Raymond³², A.L. Read¹²⁰, N.P. Readioff⁷⁶, M. Reale^{75a,75b}, D.M. Rebuzzi^{122a,122b}, A. Redelbach¹⁷⁸, G. Redlinger²⁷, R. Reece¹³⁸, R.G. Reed^{148c}, K. Reeves⁴³, L. Rehnisch¹⁷, J. Reichert¹²³, A. Reiss⁸⁵, C. Rembser³², H. Ren^{35a}, M. Rescigno^{133a}, S. Resconi^{93a}, O.L. Rezanova^{110,c}, P. Reznicek¹³⁰, R. Rezvani⁹⁶, R. Richter¹⁰², S. Richter⁸⁰, E. Richter-Was^{40b}, O. Ricken²³, M. Ridel⁸², P. Rieck¹⁷, C.J. Riegel¹⁷⁹, J. Rieger⁵⁶, O. Rifki¹¹⁴, M. Rijssenbeek¹⁵¹, A. Rimoldi^{122a,122b}, M. Rimoldi¹⁸, L. Rinaldi^{22a}, B. Ristić⁵¹, E. Ritsch³², I. Riu¹³, F. Rizatdinova¹¹⁵, E. Rizvi⁷⁸, C. Rizzi¹³, S.H. Robertson^{89,m}, A. Robichaud-Veronneau⁸⁹, D. Robinson³⁰, J.E.M. Robinson⁴⁴, A. Robson⁵⁵, C. Roda^{125a,125b}, Y. Rodina^{87,ak}, A. Rodriguez Perez¹³, D. Rodriguez Rodriguez¹⁷¹, S. Roe³², C.S. Rogan⁵⁸, O. Røhne¹²⁰, A. Romaniouk⁹⁹, M. Romano^{22a,22b}, S.M. Romano Saez³⁶, E. Romero Adam¹⁷¹, N. Rompotis¹³⁹, M. Ronzani⁵⁰, L. Roos⁸², E. Ros¹⁷¹, S. Rosati^{133a}, K. Rosbach⁵⁰, P. Rose¹³⁸, N.-A. Rosien⁵⁶, V. Rossetti^{149a,149b}, E. Rossi^{105a,105b}, L.P. Rossi^{52a}, J.H.N. Rosten³⁰, R. Rosten¹³⁹, M. Rotaru^{28b}, I. Roth¹⁷⁶, J. Rothberg¹³⁹, D. Rousseau¹¹⁸, A. Rozanov⁸⁷, Y. Rozen¹⁵⁵, X. Ruan^{148c}, F. Rubbo¹⁴⁶, M.S. Rudolph¹⁶², F. Rühr⁵⁰, A. Ruiz-Martinez³¹, Z. Rurikova⁵⁰, N.A. Rusakovitch⁶⁷, A. Ruschke¹⁰¹, H.L. Russell¹³⁹, J.P. Rutherford⁷, N. Ruthmann³², Y.F. Ryabov¹²⁴, M. Rybar¹⁷⁰, G. Rybkin¹¹⁸, S. Ryu⁶, A. Ryzhov¹³¹, G.F. Rzehorz⁵⁶, A.F. Saavedra¹⁵³, G. Sabato¹⁰⁸, S. Sacerdoti²⁹, H.F.-W. Sadrozinski¹³⁸, R. Sadykov⁶⁷, F. Safai Tehrani^{133a}, P. Saha¹⁰⁹, M. Sahinsoy^{60a}, M. Saimpert¹³⁷, T. Saito¹⁵⁸, H. Sakamoto¹⁵⁸, Y. Sakurai¹⁷⁵, G. Salamanna^{135a,135b}, A. Salamon^{134a,134b},

J.E. Salazar Loyola^{34b}, D. Salek¹⁰⁸, P.H. Sales De Bruin¹³⁹, D. Salihagic¹⁰², A. Salnikov¹⁴⁶, J. Salt¹⁷¹, D. Salvatore^{39a,39b}, F. Salvatore¹⁵², A. Salvucci^{62a,62b,62c}, A. Salzburger³², D. Sammel⁵⁰, D. Sampsonidis¹⁵⁷, J. Sánchez¹⁷¹, V. Sanchez Martinez¹⁷¹, A. Sanchez Pineda^{105a,105b}, H. Sandaker¹²⁰, R.L. Sandbach⁷⁸, H.G. Sander⁸⁵, M. Sandhoff¹⁷⁹, C. Sandoval²¹, D.P.C. Sankey¹³², M. Sannino^{52a,52b}, A. Sansoni⁴⁹, C. Santoni³⁶, R. Santonico^{134a,134b}, H. Santos^{127a}, I. Santoyo Castillo¹⁵², K. Sapp¹²⁶, A. Sapronov⁶⁷, J.G. Saraiva^{127a,127d}, B. Sarrazin²³, O. Sasaki⁶⁸, K. Sato¹⁶⁵, E. Sauvan⁵, G. Savage⁷⁹, P. Savard^{162,d}, N. Savic¹⁰², C. Sawyer¹³², L. Sawyer^{81,r}, J. Saxon³³, C. Sbarra^{22a}, A. Sbrizzi^{22a,22b}, T. Scanlon⁸⁰, D.A. Scannicchio¹⁶⁷, M. Scarcella¹⁵³, V. Scarfone^{39a,39b}, J. Schaarschmidt¹⁷⁶, P. Schacht¹⁰², B.M. Schachtner¹⁰¹, D. Schaefer³², L. Schaefer¹²³, R. Schaefer⁴⁴, J. Schaeffer⁸⁵, S. Schaepe²³, S. Schaetzel^{60b}, U. Schäfer⁸⁵, A.C. Schaffer¹¹⁸, D. Schaile¹⁰¹, R.D. Schamberger¹⁵¹, V. Scharf^{60a}, V.A. Schegelsky¹²⁴, D. Scheirich¹³⁰, M. Schernau¹⁶⁷, C. Schiavi^{52a,52b}, S. Schier¹³⁸, C. Schillo⁵⁰, M. Schioppa^{39a,39b}, S. Schlenker³², K.R. Schmidt-Sommerfeld¹⁰², K. Schmieden³², C. Schmitt⁸⁵, S. Schmitt⁴⁴, S. Schmitz⁸⁵, B. Schneider^{164a}, U. Schnoor⁵⁰, L. Schoeffel¹³⁷, A. Schoening^{60b}, B.D. Schoenrock⁹², E. Schopf²³, M. Schott⁸⁵, J.F.P. Schouwenberg¹⁰⁷, J. Schovancova⁸, S. Schramm⁵¹, M. Schreyer¹⁷⁸, N. Schuh⁸⁵, A. Schulte⁸⁵, M.J. Schultens²³, H.-C. Schultz-Coulon^{60a}, H. Schulz¹⁷, M. Schumacher⁵⁰, B.A. Schumm¹³⁸, Ph. Schune¹³⁷, A. Schwartzman¹⁴⁶, T.A. Schwarz⁹¹, H. Schweiger⁸⁶, Ph. Schwemling¹³⁷, R. Schwienhorst⁹², J. Schwindling¹³⁷, T. Schwindt²³, G. Sciolla²⁵, F. Scuri^{125a,125b}, F. Scutti⁹⁰, J. Searcy⁹¹, P. Seema²³, S.C. Seidel¹⁰⁶, A. Seiden¹³⁸, F. Seifert¹²⁹, J.M. Seixas^{26a}, G. Sekhniaidze^{105a}, K. Sekhon⁹¹, S.J. Sekula⁴², D.M. Seliverstov^{124,*}, N. Semprini-Cesari^{22a,22b}, C. Serfon¹²⁰, L. Serin¹¹⁸, L. Serkin^{168a,168b}, M. Sessa^{135a,135b}, R. Seuster¹⁷³, H. Severini¹¹⁴, T. Sfiligoi⁷⁷, F. Sforza³², A. Sfyrla⁵¹, E. Shabalina⁵⁶, N.W. Shaikh^{149a,149b}, L.Y. Shan^{35a}, R. Shang¹⁷⁰, J.T. Shank²⁴, M. Shapiro¹⁶, P.B. Shatalov⁹⁸, K. Shaw^{168a,168b}, S.M. Shaw⁸⁶, A. Shcherbakova^{149a,149b}, C.Y. Shehu¹⁵², P. Sherwood⁸⁰, L. Shi^{154,al}, S. Shimizu⁶⁹, C.O. Shimmin¹⁶⁷, M. Shimojima¹⁰³, S. Shirabe⁷², M. Shiyakova^{67,am}, A. Shmeleva⁹⁷, D. Shoaleh Saadi⁹⁶, M.J. Shochet³³, S. Shojaii^{93a,93b}, D.R. Shope¹¹⁴, S. Shrestha¹¹², E. Shulga⁹⁹, M.A. Shupe⁷, P. Sicho¹²⁸, A.M. Sickles¹⁷⁰, P.E. Sidebo¹⁵⁰, O. Sidiropoulou¹⁷⁸, D. Sidorov¹¹⁵, A. Sidoti^{22a,22b}, F. Siegert⁴⁶, Dj. Sijacki¹⁴, J. Silva^{127a,127d}, S.B. Silverstein^{149a}, V. Simak¹²⁹, Lj. Simic¹⁴, S. Simion¹¹⁸, E. Simioni⁸⁵, B. Simmons⁸⁰, D. Simon³⁶, M. Simon⁸⁵, P. Sinervo¹⁶², N.B. Sinev¹¹⁷, M. Sioli^{22a,22b}, G. Siragusa¹⁷⁸, S.Yu. Sivoklov¹⁰⁰, J. Sjölin^{149a,149b}, M.B. Skinner⁷⁴, H.P. Skottowe⁵⁸, P. Skubic¹¹⁴, M. Slater¹⁹, T. Slavicek¹²⁹, M. Slawinska¹⁰⁸, K. Sliwa¹⁶⁶, R. Slovak¹³⁰, V. Smakhtin¹⁷⁶, B.H. Smart⁵, L. Smestad¹⁵, J. Smiesko^{147a}, S.Yu. Smirnov⁹⁹, Y. Smirnov⁹⁹, L.N. Smirnova^{100,an}, O. Smirnova⁸³, M.N.K. Smith³⁷, R.W. Smith³⁷, M. Smizanska⁷⁴, K. Smolek¹²⁹, A.A. Snesarev⁹⁷, I.M. Snyder¹¹⁷, S. Snyder²⁷, R. Sobie^{173,m}, F. Socher⁴⁶, A. Soffer¹⁵⁶, D.A. Soh¹⁵⁴, G. Sokhrannyi⁷⁷, C.A. Solans Sanchez³², M. Solar¹²⁹, E.Yu. Soldatov⁹⁹, U. Soldevila¹⁷¹, A.A. Solodkov¹³¹, A. Soloshenko⁶⁷, O.V. Solovyanov¹³¹, V. Solovyev¹²⁴, P. Sommer⁵⁰, H. Son¹⁶⁶, H.Y. Song^{59,ao}, A. Sood¹⁶, A. Sopczak¹²⁹, V. Sopko¹²⁹, V. Sorin¹³, D. Sosa^{60b}, C.L. Sotiropoulou^{125a,125b}, R. Soualah^{168a,168c}, A.M. Soukharev^{110,c}, D. South⁴⁴, B.C. Sowden⁷⁹, S. Spagnolo^{75a,75b}, M. Spalla^{125a,125b}, M. Spangenberg¹⁷⁴, F. Spanò⁷⁹, D. Sperlich¹⁷, F. Spettel¹⁰², R. Spighi^{22a}, G. Spigo³², L.A. Spiller⁹⁰, M. Spousta¹³⁰, R.D. St. Denis^{55,*}, A. Stabile^{93a}, R. Stamen^{60a}, S. Stamm¹⁷, E. Stanecka⁴¹, R.W. Stanek⁶, C. Stanescu^{135a}, M. Stanescu-Bellu⁴⁴, M.M. Stanitzki⁴⁴, S. Stapnes¹²⁰, E.A. Starchenko¹³¹, G.H. Stark³³, J. Stark⁵⁷, P. Staroba¹²⁸, P. Starovoitov^{60a}, S. Stärz³², R. Staszewski⁴¹, P. Steinberg²⁷, B. Stelzer¹⁴⁵, H.J. Stelzer³², O. Stelzer-Chilton^{164a}, H. Stenzel⁵⁴, G.A. Stewart⁵⁵, J.A. Stillings²³, M.C. Stockton⁸⁹, M. Stoebe⁸⁹, G. Stoicea^{28b}, P. Stolte⁵⁶, S. Stonjek¹⁰², A.R. Stradling⁸, A. Straessner⁴⁶, M.E. Stramaglia¹⁸, J. Strandberg¹⁵⁰, S. Strandberg^{149a,149b}, A. Strandlie¹²⁰, M. Strauss¹¹⁴, P. Strizenec^{147b}, R. Ströhmer¹⁷⁸, D.M. Strom¹¹⁷, R. Stroynowski⁴², A. Strubig¹⁰⁷, S.A. Stucci²⁷, B. Stugu¹⁵, N.A. Styles⁴⁴, D. Su¹⁴⁶, J. Su¹²⁶, S. Suchek^{60a}, Y. Sugaya¹¹⁹, M. Suk¹²⁹, V.V. Sulin⁹⁷, S. Sultansoy^{4c}, T. Sumida⁷⁰, S. Sun⁵⁸, X. Sun^{35a}, J.E. Sundermann⁵⁰, K. Suruliz¹⁵², G. Susinno^{39a,39b}, M.R. Sutton¹⁵², S. Suzuki⁶⁸, M. Svatos¹²⁸, M. Swiatlowski³³, I. Sykora^{147a}, T. Sykora¹³⁰, D. Ta⁵⁰, C. Taccini^{135a,135b}, K. Tackmann⁴⁴, J. Taenzer¹⁶², A. Taffard¹⁶⁷, R. Tahirout^{164a}, N. Taiblum¹⁵⁶, H. Takai²⁷, R. Takashima⁷¹, T. Takeshita¹⁴³, Y. Takubo⁶⁸, M. Talby⁸⁷, A.A. Talyshv^{110,c}, K.G. Tan⁹⁰, J. Tanaka¹⁵⁸, M. Tanaka¹⁶⁰, R. Tanaka¹¹⁸, S. Tanaka⁶⁸, R. Tanioka⁶⁹, B.B. Tannenwald¹¹², S. Tapia Araya^{34b}, S. Tapprogge⁸⁵, S. Tarem¹⁵⁵, G.F. Tartarelli^{93a}, P. Tas¹³⁰, M. Tasevsky¹²⁸, T. Tashiro⁷⁰, E. Tassi^{39a,39b}, A. Tavares Delgado^{127a,127b}, Y. Tayalati^{136e}, A.C. Taylor¹⁰⁶, G.N. Taylor⁹⁰, P.T.E. Taylor⁹⁰, W. Taylor^{164b}, F.A. Teischinger³²,

P. Teixeira-Dias⁷⁹, K.K. Temming⁵⁰, D. Temple¹⁴⁵, H. Ten Kate³², P.K. Teng¹⁵⁴, J.J. Teoh¹¹⁹, F. Tepel¹⁷⁹, S. Terada⁶⁸, K. Terashi¹⁵⁸, J. Terron⁸⁴, S. Terzo¹³, M. Testa⁴⁹, R.J. Teuscher^{162,m}, T. Theveneaux-Pelzer⁸⁷, J.P. Thomas¹⁹, J. Thomas-Wilsker⁷⁹, E.N. Thompson³⁷, P.D. Thompson¹⁹, A.S. Thompson⁵⁵, L.A. Thomsen¹⁸⁰, E. Thomson¹²³, M. Thomson³⁰, M.J. Tibbetts¹⁶, R.E. Ticse Torres⁸⁷, V.O. Tikhomirov^{97,ap}, Yu.A. Tikhonov^{110,c}, S. Timoshenko⁹⁹, P. Tipton¹⁸⁰, S. Tisserant⁸⁷, K. Todome¹⁶⁰, T. Todorov^{5,*}, S. Todorova-Nova¹³⁰, J. Tojo⁷², S. Tokár^{147a}, K. Tokushuku⁶⁸, E. Tolley⁵⁸, L. Tomlinson⁸⁶, M. Tomoto¹⁰⁴, L. Tompkins^{146,aq}, K. Toms¹⁰⁶, B. Tong⁵⁸, P. Tornambe⁵⁰, E. Torrence¹¹⁷, H. Torres¹⁴⁵, E. Torró Pastor¹³⁹, J. Toth^{87,ar}, F. Touchard⁸⁷, D.R. Tovey¹⁴², T. Trefzger¹⁷⁸, A. Tricoli²⁷, I.M. Trigger^{164a}, S. Trincaz-Duvoid⁸², M.F. Tripiana¹³, W. Trischuk¹⁶², B. Trocmé⁵⁷, A. Trofymov⁴⁴, C. Troncon^{93a}, M. Trottier-McDonald¹⁶, M. Trovatelli¹⁷³, L. Truong^{168a,168c}, M. Trzebinski⁴¹, A. Trzupek⁴¹, J.C.-L. Tseng¹²¹, P.V. Tsiareshka⁹⁴, G. Tsipolitis¹⁰, N. Tsirintanis⁹, S. Tsiskaridze¹³, V. Tsiskaridze⁵⁰, E.G. Tskhadadze^{53a}, K.M. Tsui^{62a}, I.I. Tsukerman⁹⁸, V. Tsulaia¹⁶, S. Tsuno⁶⁸, D. Tsybychev¹⁵¹, Y. Tu^{62b}, A. Tudorache^{28b}, V. Tudorache^{28b}, A.N. Tuna⁵⁸, S.A. Tupputi^{22a,22b}, S. Turchikhin⁶⁷, D. Turecek¹²⁹, D. Turgeman¹⁷⁶, R. Turra^{93a,93b}, P.M. Tuts³⁷, M. Tyndel¹³², G. Uccielli^{22a,22b}, I. Ueda¹⁵⁸, M. Ughetto^{149a,149b}, F. Ukegawa¹⁶⁵, G. Unal³², A. Undrus²⁷, G. Unel¹⁶⁷, F.C. Ungaro⁹⁰, Y. Unno⁶⁸, C. Unverdorben¹⁰¹, J. Urban^{147b}, P. Urquijo⁹⁰, P. Urrejola⁸⁵, G. Usai⁸, L. Vacavant⁸⁷, V. Vacek¹²⁹, B. Vachon⁸⁹, C. Valderanis¹⁰¹, E. Valdes Santurio^{149a,149b}, N. Valencic¹⁰⁸, S. Valentini^{22a,22b}, A. Valero¹⁷¹, L. Valery¹³, S. Valkar¹³⁰, J.A. Valls Ferrer¹⁷¹, W. Van Den Wollenberg¹⁰⁸, P.C. Van Der Deijl¹⁰⁸, H. van der Graaf¹⁰⁸, N. van Eldik¹⁵⁵, P. van Gemmeren⁶, J. Van Nieuwkoop¹⁴⁵, I. van Vulpen¹⁰⁸, M.C. van Woerden³², M. Vanadia^{133a,133b}, W. Vandelli³², R. Vanguri¹²³, A. Vaniachine¹⁶¹, P. Vankov¹⁰⁸, G. Vardanyan¹⁸¹, R. Vari^{133a}, E.W. Varnes⁷, T. Varol⁴², D. Varouchas⁸², A. Vartapetian⁸, K.E. Varvell¹⁵³, J.G. Vasquez¹⁸⁰, G.A. Vasquez^{34b}, F. Vazeille³⁶, T. Vazquez Schroeder⁸⁹, J. Veatch⁵⁶, V. Veeraraghavan⁷, L.M. Veloce¹⁶², F. Veloso^{127a,127c}, S. Veneziano^{133a}, A. Ventura^{75a,75b}, M. Venturi¹⁷³, N. Venturi¹⁶², A. Venturini²⁵, V. Vercesi^{122a}, M. Verducci^{133a,133b}, W. Verkerke¹⁰⁸, J.C. Vermeulen¹⁰⁸, A. Vest^{46,as}, M.C. Vetterli^{145,d}, O. Viazlo⁸³, I. Vichou^{170,*}, T. Vickey¹⁴², O.E. Vickey Boeriu¹⁴², G.H.A. Viehhauser¹²¹, S. Viel¹⁶, L. Vigani¹²¹, M. Villa^{22a,22b}, M. Villaplana Perez^{93a,93b}, E. Vilucchi⁴⁹, M.G. Vincker³¹, V.B. Vinogradov⁶⁷, C. Vittori^{22a,22b}, I. Vivarelli¹⁵², S. Vlachos¹⁰, M. Vlasak¹²⁹, M. Vogel¹⁷⁹, P. Vokac¹²⁹, G. Volpi^{125a,125b}, M. Volpi⁹⁰, H. von der Schmitt¹⁰², E. von Toerne²³, V. Vorobel¹³⁰, K. Vorobev⁹⁹, M. Vos¹⁷¹, R. Voss³², J.H. Vosseveld⁷⁶, N. Vranjes¹⁴, M. Vranjes Milosavljevic¹⁴, V. Vrba¹²⁸, M. Vreeswijk¹⁰⁸, R. Vuillermet³², I. Vukotic³³, Z. Vykydal¹²⁹, P. Wagner²³, W. Wagner¹⁷⁹, H. Wahlberg⁷³, S. Wahrmund⁴⁶, J. Wakabayashi¹⁰⁴, J. Walder⁷⁴, R. Walker¹⁰¹, W. Walkowiak¹⁴⁴, V. Wallangen^{149a,149b}, C. Wang^{35b}, C. Wang^{140,87}, F. Wang¹⁷⁷, H. Wang¹⁶, H. Wang⁴², J. Wang⁴⁴, J. Wang¹⁵³, K. Wang⁸⁹, R. Wang⁶, S.M. Wang¹⁵⁴, T. Wang²³, T. Wang³⁷, W. Wang⁵⁹, X. Wang¹⁸⁰, C. Wanotayaroj¹¹⁷, A. Warburton⁸⁹, C.P. Ward³⁰, D.R. Wardrope⁸⁰, A. Washbrook⁴⁸, P.M. Watkins¹⁹, A.T. Watson¹⁹, M.F. Watson¹⁹, G. Watts¹³⁹, S. Watts⁸⁶, B.M. Waugh⁸⁰, S. Webb⁸⁵, M.S. Weber¹⁸, S.W. Weber¹⁷⁸, S.A. Weber³¹, J.S. Webster⁶, A.R. Weidberg¹²¹, B. Weinert⁶³, J. Weingarten⁵⁶, C. Weiser⁵⁰, H. Weits¹⁰⁸, P.S. Wells³², T. Wenaus²⁷, T. Wengler³², S. Wenig³², N. Wermes²³, M. Werner⁵⁰, M.D. Werner⁶⁶, P. Werner³², M. Wessels^{60a}, J. Wetter¹⁶⁶, K. Whalen¹¹⁷, N.L. Whallon¹³⁹, A.M. Wharton⁷⁴, A. White⁸, M.J. White¹, R. White^{34b}, D. Whiteson¹⁶⁷, F.J. Wickens¹³², W. Wiedenmann¹⁷⁷, M. Wielers¹³², C. Wigglesworth³⁸, L.A.M. Wiik-Fuchs²³, A. Wildauer¹⁰², F. Wilk⁸⁶, H.G. Wilkens³², H.H. Williams¹²³, S. Williams¹⁰⁸, C. Willis⁹², S. Willocq⁸⁸, J.A. Wilson¹⁹, I. Wingerter-Seez⁵, F. Winklmeier¹¹⁷, O.J. Winston¹⁵², B.T. Winter²³, M. Wittgen¹⁴⁶, J. Wittkowski¹⁰¹, T.M.H. Wolf¹⁰⁸, M.W. Wolter⁴¹, H. Wolters^{127a,127c}, S.D. Worm¹³², B.K. Wosiek⁴¹, J. Wotschack³², M.J. Woudstra⁸⁶, K.W. Wozniak⁴¹, M. Wu⁵⁷, M. Wu³³, S.L. Wu¹⁷⁷, X. Wu⁵¹, Y. Wu⁹¹, T.R. Wyatt⁸⁶, B.M. Wynne⁴⁸, S. Xella³⁸, D. Xu^{35a}, L. Xu²⁷, B. Yabsley¹⁵³, S. Yacoob^{148a}, D. Yamaguchi¹⁶⁰, Y. Yamaguchi¹¹⁹, A. Yamamoto⁶⁸, S. Yamamoto¹⁵⁸, T. Yamanaka¹⁵⁸, K. Yamauchi¹⁰⁴, Y. Yamazaki⁶⁹, Z. Yan²⁴, H. Yang¹⁴¹, H. Yang¹⁷⁷, Y. Yang¹⁵⁴, Z. Yang¹⁵, W.-M. Yao¹⁶, Y.C. Yap⁸², Y. Yasu⁶⁸, E. Yatsenko⁵, K.H. Yau Wong²³, J. Ye⁴², S. Ye²⁷, I. Yeletsikh⁶⁷, A.L. Yen⁵⁸, E. Yildirim⁸⁵, K. Yorita¹⁷⁵, R. Yoshida⁶, K. Yoshihara¹²³, C. Young¹⁴⁶, C.J.S. Young³², S. Youssef²⁴, D.R. Yu¹⁶, J. Yu⁸, J.M. Yu⁹¹, J. Yu⁶⁶, L. Yuan⁶⁹, S.P.Y. Yuen²³, I. Yusuf^{30,at}, B. Zabinski⁴¹, R. Zaidan⁶⁵, A.M. Zaitsev^{131,ae}, N. Zakharchuk⁴⁴, J. Zalieckas¹⁵, A. Zaman¹⁵¹, S. Zambito⁵⁸, L. Zanello^{133a,133b}, D. Zanzi⁹⁰, C. Zeitnitz¹⁷⁹, M. Zeman¹²⁹, A. Zemla^{40a}, J.C. Zeng¹⁷⁰, Q. Zeng¹⁴⁶, K. Zengel²⁵, O. Zenin¹³¹,

T. Ženiš^{147a}, D. Zerwas¹¹⁸, D. Zhang⁹¹, F. Zhang¹⁷⁷, G. Zhang^{59,ao}, H. Zhang^{35b}, J. Zhang⁶, L. Zhang⁵⁰, R. Zhang²³, R. Zhang^{59,au}, X. Zhang¹⁴⁰, Z. Zhang¹¹⁸, X. Zhao⁴², Y. Zhao¹⁴⁰, Z. Zhao⁵⁹, A. Zhemchugov⁶⁷, J. Zhong¹²¹, B. Zhou⁹¹, C. Zhou¹⁷⁷, L. Zhou³⁷, L. Zhou⁴², M. Zhou¹⁵¹, N. Zhou^{35c}, C.G. Zhu¹⁴⁰, H. Zhu^{35a}, J. Zhu⁹¹, Y. Zhu⁵⁹, X. Zhuang^{35a}, K. Zhukov⁹⁷, A. Zibell¹⁷⁸, D. Zieminska⁶³, N.I. Zimine⁶⁷, C. Zimmermann⁸⁵, S. Zimmermann⁵⁰, Z. Zinonos⁵⁶, M. Zinser⁸⁵, M. Ziolkowski¹⁴⁴, L. Živković¹⁴, G. Zobernig¹⁷⁷, A. Zoccoli^{22a,22b}, M. zur Nedden¹⁷, L. Zwalinski³²

¹ Department of Physics, University of Adelaide, Adelaide, Australia

² Physics Department, SUNY Albany, Albany, NY, United States

³ Department of Physics, University of Alberta, Edmonton, AB, Canada

⁴ (a) Department of Physics, Ankara University, Ankara; (b) Istanbul Aydin University, Istanbul; (c) Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey

⁵ LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France

⁶ High Energy Physics Division, Argonne National Laboratory, Argonne, IL, United States

⁷ Department of Physics, University of Arizona, Tucson, AZ, United States

⁸ Department of Physics, The University of Texas at Arlington, Arlington, TX, United States

⁹ Physics Department, University of Athens, Athens, Greece

¹⁰ Physics Department, National Technical University of Athens, Zografou, Greece

¹¹ Department of Physics, The University of Texas at Austin, Austin, TX, United States

¹² Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

¹³ Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain

¹⁴ Institute of Physics, University of Belgrade, Belgrade, Serbia

¹⁵ Department for Physics and Technology, University of Bergen, Bergen, Norway

¹⁶ Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, United States

¹⁷ Department of Physics, Humboldt University, Berlin, Germany

¹⁸ Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland

¹⁹ School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom

²⁰ (a) Department of Physics, Bogazici University, Istanbul; (b) Department of Physics Engineering, Gaziantep University, Gaziantep; (d) Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul; (e) Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey

²¹ Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia

²² (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy

²³ Physikalisches Institut, University of Bonn, Bonn, Germany

²⁴ Department of Physics, Boston University, Boston, MA, United States

²⁵ Department of Physics, Brandeis University, Waltham, MA, United States

²⁶ (a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (b) Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; (d) Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil

²⁷ Physics Department, Brookhaven National Laboratory, Upton, NY, United States

²⁸ (a) Transilvania University of Brasov, Brasov, Romania; (b) National Institute of Physics and Nuclear Engineering, Bucharest; (c) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; (d) University Politehnica Bucharest, Bucharest; (e) West University in Timisoara, Timisoara, Romania

²⁹ Departamento de Fisica, Universidad de Buenos Aires, Buenos Aires, Argentina

³⁰ Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom

³¹ Department of Physics, Carleton University, Ottawa, ON, Canada

³² CERN, Geneva, Switzerland

³³ Enrico Fermi Institute, University of Chicago, Chicago, IL, United States

³⁴ (a) Departamento de Fisica, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Fisica, Universidad Técnica Federico Santa María, Valparaíso, Chile

³⁵ (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Physics, Nanjing University, Jiangsu; (c) Physics Department, Tsinghua University, Beijing 100084, China

³⁶ Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France

³⁷ Nevis Laboratory, Columbia University, Irvington, NY, United States

³⁸ Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark

³⁹ (a) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; (b) Dipartimento di Fisica, Università della Calabria, Rende, Italy

⁴⁰ (a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; (b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland

⁴¹ Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland

⁴² Physics Department, Southern Methodist University, Dallas, TX, United States

⁴³ Physics Department, University of Texas at Dallas, Richardson, TX, United States

⁴⁴ DESY, Hamburg and Zeuthen, Germany

⁴⁵ Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany

⁴⁶ Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany

⁴⁷ Department of Physics, Duke University, Durham, NC, United States

⁴⁸ SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom

⁴⁹ INFN Laboratori Nazionali di Frascati, Frascati, Italy

⁵⁰ Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany

⁵¹ Section de Physique, Université de Genève, Geneva, Switzerland

⁵² (a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy

⁵³ (a) E. Andronikashvili Institute of Physics, Iv. Javakishvili Tbilisi State University, Tbilisi; (b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia

⁵⁴ II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany

⁵⁵ SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom

⁵⁶ II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany

⁵⁷ Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France

⁵⁸ Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, United States

⁵⁹ Department of Modern Physics, University of Science and Technology of China, Anhui, China

⁶⁰ (a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (c) ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany

⁶¹ Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan

⁶² (a) Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong; (b) Department of Physics, The University of Hong Kong, Hong Kong; (c) Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China

- ⁶³ Department of Physics, Indiana University, Bloomington, IN, United States
- ⁶⁴ Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- ⁶⁵ University of Iowa, Iowa City, IA, United States
- ⁶⁶ Department of Physics and Astronomy, Iowa State University, Ames, IA, United States
- ⁶⁷ Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
- ⁶⁸ KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- ⁶⁹ Graduate School of Science, Kobe University, Kobe, Japan
- ⁷⁰ Faculty of Science, Kyoto University, Kyoto, Japan
- ⁷¹ Kyoto University of Education, Kyoto, Japan
- ⁷² Department of Physics, Kyushu University, Fukuoka, Japan
- ⁷³ Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- ⁷⁴ Physics Department, Lancaster University, Lancaster, United Kingdom
- ⁷⁵ ^(a) INFN Sezione di Lecce; ^(b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- ⁷⁶ Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- ⁷⁷ Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
- ⁷⁸ School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
- ⁷⁹ Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
- ⁸⁰ Department of Physics and Astronomy, University College London, London, United Kingdom
- ⁸¹ Louisiana Tech University, Ruston, LA, United States
- ⁸² Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- ⁸³ Fysiska institutionen, Lunds universitet, Lund, Sweden
- ⁸⁴ Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain
- ⁸⁵ Institut für Physik, Universität Mainz, Mainz, Germany
- ⁸⁶ School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- ⁸⁷ CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- ⁸⁸ Department of Physics, University of Massachusetts, Amherst, MA, United States
- ⁸⁹ Department of Physics, McGill University, Montreal, QC, Canada
- ⁹⁰ School of Physics, University of Melbourne, Victoria, Australia
- ⁹¹ Department of Physics, The University of Michigan, Ann Arbor, MI, United States
- ⁹² Department of Physics and Astronomy, Michigan State University, East Lansing, MI, United States
- ⁹³ ^(a) INFN Sezione di Milano; ^(b) Dipartimento di Fisica, Università di Milano, Milano, Italy
- ⁹⁴ B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
- ⁹⁵ National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Belarus
- ⁹⁶ Group of Particle Physics, University of Montreal, Montreal, QC, Canada
- ⁹⁷ P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
- ⁹⁸ Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- ⁹⁹ National Research Nuclear University MEPhI, Moscow, Russia
- ¹⁰⁰ D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
- ¹⁰¹ Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- ¹⁰² Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- ¹⁰³ Nagasaki Institute of Applied Science, Nagasaki, Japan
- ¹⁰⁴ Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
- ¹⁰⁵ ^(a) INFN Sezione di Napoli; ^(b) Dipartimento di Fisica, Università di Napoli, Napoli, Italy
- ¹⁰⁶ Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States
- ¹⁰⁷ Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- ¹⁰⁸ Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- ¹⁰⁹ Department of Physics, Northern Illinois University, DeKalb, IL, United States
- ¹¹⁰ Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
- ¹¹¹ Department of Physics, New York University, New York, NY, United States
- ¹¹² Ohio State University, Columbus, OH, United States
- ¹¹³ Faculty of Science, Okayama University, Okayama, Japan
- ¹¹⁴ Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, United States
- ¹¹⁵ Department of Physics, Oklahoma State University, Stillwater, OK, United States
- ¹¹⁶ Palacký University, RCPM, Olomouc, Czech Republic
- ¹¹⁷ Center for High Energy Physics, University of Oregon, Eugene, OR, United States
- ¹¹⁸ LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
- ¹¹⁹ Graduate School of Science, Osaka University, Osaka, Japan
- ¹²⁰ Department of Physics, University of Oslo, Oslo, Norway
- ¹²¹ Department of Physics, Oxford University, Oxford, United Kingdom
- ¹²² ^(a) INFN Sezione di Pavia; ^(b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- ¹²³ Department of Physics, University of Pennsylvania, Philadelphia, PA, United States
- ¹²⁴ National Research Centre "Kurchatov Institute" B.P. Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia
- ¹²⁵ ^(a) INFN Sezione di Pisa; ^(b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- ¹²⁶ Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, United States
- ¹²⁷ ^(a) Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa; ^(b) Faculdade de Ciências, Universidade de Lisboa, Lisboa; ^(c) Department of Physics, University of Coimbra, Coimbra; ^(d) Centro de Física Nuclear da Universidade de Lisboa, Lisboa; ^(e) Departamento de Física, Universidade do Minho, Braga; ^(f) Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain); ^(g) Dep Física and CEFITEC de Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
- ¹²⁸ Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
- ¹²⁹ Czech Technical University in Prague, Praha, Czech Republic
- ¹³⁰ Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
- ¹³¹ State Research Center Institute for High Energy Physics (Protvino), NRC KI, Russia
- ¹³² Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- ¹³³ ^(a) INFN Sezione di Roma; ^(b) Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
- ¹³⁴ ^(a) INFN Sezione di Roma Tor Vergata; ^(b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- ¹³⁵ ^(a) INFN Sezione di Roma Tre; ^(b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
- ¹³⁶ ^(a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; ^(b) Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat; ^(c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; ^(d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; ^(e) Faculté des sciences, Université Mohammed V, Rabat, Morocco
- ¹³⁷ DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France

- ¹³⁸ Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, United States
- ¹³⁹ Department of Physics, University of Washington, Seattle, WA, United States
- ¹⁴⁰ School of Physics, Shandong University, Shandong, China
- ¹⁴¹ Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai, China ^{av}
- ¹⁴² Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
- ¹⁴³ Department of Physics, Shinshu University, Nagano, Japan
- ¹⁴⁴ Fachbereich Physik, Universität Siegen, Siegen, Germany
- ¹⁴⁵ Department of Physics, Simon Fraser University, Burnaby, BC, Canada
- ¹⁴⁶ SLAC National Accelerator Laboratory, Stanford, CA, United States
- ¹⁴⁷ ^(a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; ^(b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
- ¹⁴⁸ ^(a) Department of Physics, University of Cape Town, Cape Town; ^(b) Department of Physics, University of Johannesburg, Johannesburg; ^(c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
- ¹⁴⁹ ^(a) Department of Physics, Stockholm University; ^(b) The Oskar Klein Centre, Stockholm, Sweden
- ¹⁵⁰ Physics Department, Royal Institute of Technology, Stockholm, Sweden
- ¹⁵¹ Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, NY, United States
- ¹⁵² Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
- ¹⁵³ School of Physics, University of Sydney, Sydney, Australia
- ¹⁵⁴ Institute of Physics, Academia Sinica, Taipei, Taiwan
- ¹⁵⁵ Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
- ¹⁵⁶ Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
- ¹⁵⁷ Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
- ¹⁵⁸ International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
- ¹⁵⁹ Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
- ¹⁶⁰ Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
- ¹⁶¹ Tomsk State University, Tomsk, Russia
- ¹⁶² Department of Physics, University of Toronto, Toronto, ON, Canada
- ¹⁶³ ^(a) INFN-TIFPA; ^(b) University of Trento, Trento, Italy
- ¹⁶⁴ ^(a) TRIUMF, Vancouver, BC; ^(b) Department of Physics and Astronomy, York University, Toronto, ON, Canada
- ¹⁶⁵ Faculty of Pure and Applied Sciences, and Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Japan
- ¹⁶⁶ Department of Physics and Astronomy, Tufts University, Medford, MA, United States
- ¹⁶⁷ Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States
- ¹⁶⁸ ^(a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; ^(b) ICTP, Trieste; ^(c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
- ¹⁶⁹ Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
- ¹⁷⁰ Department of Physics, University of Illinois, Urbana, IL, United States
- ¹⁷¹ Instituto de Física Corpuscular (IFIC) and Departamento de Física Atomica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
- ¹⁷² Department of Physics, University of British Columbia, Vancouver, BC, Canada
- ¹⁷³ Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada
- ¹⁷⁴ Department of Physics, University of Warwick, Coventry, United Kingdom
- ¹⁷⁵ Waseda University, Tokyo, Japan
- ¹⁷⁶ Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
- ¹⁷⁷ Department of Physics, University of Wisconsin, Madison, WI, United States
- ¹⁷⁸ Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
- ¹⁷⁹ Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
- ¹⁸⁰ Department of Physics, Yale University, New Haven, CT, United States
- ¹⁸¹ Yerevan Physics Institute, Yerevan, Armenia
- ¹⁸² Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

^a Also at Department of Physics, King's College London, London, United Kingdom.

^b Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

^c Also at Novosibirsk State University, Novosibirsk, Russia.

^d Also at TRIUMF, Vancouver BC, Canada.

^e Also at Department of Physics & Astronomy, University of Louisville, Louisville, KY, United States.

^f Also at Physics Department, An-Najah National University, Nablus, Palestine.

^g Also at Department of Physics, California State University, Fresno, CA, United States.

^h Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.

ⁱ Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain.

^j Also at Departamento de Física e Astronomia, Faculdade de Ciências, Universidade do Porto, Portugal.

^k Also at Tomsk State University, Tomsk, Russia.

^l Also at Università di Napoli Parthenope, Napoli, Italy.

^m Also at Institute of Particle Physics (IPP), Canada.

ⁿ Also at National Institute of Physics and Nuclear Engineering, Bucharest, Romania.

^o Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.

^p Also at Department of Physics, The University of Michigan, Ann Arbor, MI, United States.

^q Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa.

^r Also at Louisiana Tech University, Ruston, LA, United States.

^s Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.

^t Also at Graduate School of Science, Osaka University, Osaka, Japan.

^u Also at Department of Physics, National Tsing Hua University, Taiwan.

^v Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.

^w Also at Department of Physics, The University of Texas at Austin, Austin, TX, United States.

^x Also at CERN, Geneva, Switzerland.

^y Also at Georgian Technical University (GTU), Tbilisi, Georgia.

^z Also at O Chadai Academic Production, Ochanomizu University, Tokyo, Japan.

^{aa} Also at Manhattan College, New York, NY, United States.

^{ab} Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.

- ^{ac} Also at School of Physics, Shandong University, Shandong, China.
- ^{ad} Also at Department of Physics, California State University, Sacramento, CA, United States.
- ^{ae} Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
- ^{af} Also at Section de Physique, Université de Genève, Geneva, Switzerland.
- ^{ag} Also at Eotvos Lorand University, Budapest, Hungary.
- ^{ah} Also at Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, NY, United States.
- ^{ai} Also at International School for Advanced Studies (SISSA), Trieste, Italy.
- ^{aj} Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, United States.
- ^{ak} Also at Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain.
- ^{al} Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.
- ^{am} Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.
- ^{an} Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.
- ^{ao} Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
- ^{ap} Also at National Research Nuclear University MEPhI, Moscow, Russia.
- ^{aq} Also at Department of Physics, Stanford University, Stanford, CA, United States.
- ^{ar} Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
- ^{as} Also at Flensburg University of Applied Sciences, Flensburg, Germany.
- ^{at} Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.
- ^{au} Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
- ^{av} Also affiliated with PKU-CHEP.
- * Deceased.